A Procedure for Structural Weight Estimation of Single Stage to Orbit Launch Vehicles (Interim User’s Manual)

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September 2002
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Abstract

This is an interim user’s manual for current procedures used in the Vehicle Analysis Branch at NASA Langley Research Center, Hampton, Virginia, for launch vehicle structural subsystem weight estimation based on finite element modeling and structural analysis. The process is intended to complement traditional methods of conceptual and early preliminary structural design such as the application of empirical weight estimation relationships or application of classical engineering design equations and criteria on one dimensional “line” models. Functions of two commercially available software codes are coupled together. Vehicle modeling and analysis are done using SDRC/I-DEAS, and structural sizing is performed with the Collier Research Corp. HyperSizer program.
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1. Introduction

This document serves as an interim user’s manual for current procedures used in the Vehicle Analysis Branch at NASA Langley Research Center for launch vehicle structural subsystem weight estimation based on finite element modeling and structural analysis.

A general overview of the weight estimation procedure is presented first. It is followed by a detailed description of the procedure with recommendations on how to deal with the design process.

2. General Overview of the Weight Estimation Procedure

The process described in this report is based on application of finite element (FE) models to estimate weight of typical cylindrically shaped launch vehicles. The process is intended to complement traditional methods of structural design such as application of empirical weight estimation [1] or application of classical engineering design equations and criteria on one dimensional “line” models. Because of the requirement of fast turn-around at the early stage of vehicle design this method utilizes relatively simple three dimensional finite element models for structural weight estimation of the new and untested launch vehicle concepts.

The ultimate objective of this effort is to generate a procedure to automate structural weight estimation for new vehicle designs and to reduce the interaction required from analysts/designers to a “reasonable level” during the initial design stage. This procedure could further be integrated with other design disciplines, such as propulsion, trajectory analysis, aero and thermo analysis, into a unified code/procedure that would produce an initial launch vehicle candidate design with the low effort and in a short time.

The general outline of the procedure is shown in Figures 1 and 2. Vehicle geometry and preliminary structural weights and system weights are defined first from other sources such as The CONfiguration SIZing Program [1]. The vehicle geometry and finite element model meshing is done in I-DEAS [2]. Preliminary vehicle mass from CONSIZ is discretized and lumped to the FE model through a process which uses EXCEL spreadsheets and a JAVA program. External loads are modeled next. These are loads used to represent basic lift, thrust, control and tank pressure forces which are later combined and scaled to create vehicle design conditions. Inputs from different sources are compiled (such as from a trajectory program) and then the actual design load cases are created using a procedure based on integration of I-DEAS, EXCEL spreadsheets, text files and a JAVA program. The net result of this process is a lumped mass/mass-less shell element FE model with proper boundary conditions and static loading ready for a linear static solution.

The structural sizing part of the procedure consists of an initial sizing run which produces first estimates of vehicle stiffness and structural weight. After this, the user needs to iterate the
analysis and sizing runs until desired convergence of vehicle weight is achieved. Convergence satisfies the iterative nature of calculating new structural element sizes and letting this new element definition influence the vehicle mass and stiffness matrices. Static analysis is performed inside I-DEAS and results are exported to the sizing program. HyperSizer [3] sizes the vehicle shell panels to support internal running loads imported from I-DEAS. The outcome of this is a consistent mass shell vehicle ready to be imported back to I-DEAS for a new set of static analyses.

Once the iteration between I-DEAS and HyperSizer produces sufficiently converged vehicle structural weight, the process ends. Updated stiffened skin theoretical structural weights can then be modified from the theoretical state to the “as-built” weight and exported to other disciplines in the vehicle design process (such as back to CONSIZE).

Figure 1. General outline of the procedure for structural weight estimation
Figure 2. Graphical outline of the weight estimation procedure
3. Detailed Overview of the Weight Estimation Procedure

The whole procedure consists of the following major sub-procedures:

- Geometry and Finite Element Modeling,
- External Loads Modeling and Load Balancing,
- First Static Analysis and Structural Sizing,
- Iterative Static Analysis and Structural Sizing.

The flow chart of the detailed procedure is illustrated in Appendix A. Table 1 summarizes the software and programs used in this procedure.

Table 1. Software used to estimate vehicle weights

<table>
<thead>
<tr>
<th>Software</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-DEAS</td>
<td>Geometry and finite element modeling; static analysis.</td>
</tr>
<tr>
<td>HYPERSIZER</td>
<td>- Preliminary vehicle stiffness definition; - element sizing.</td>
</tr>
<tr>
<td>I-DEAS programs</td>
<td>Geometry and finite element meshing; physical property assignment to finite elements; lump mass distribution to finite elements. General CAD/CAE tasks.</td>
</tr>
<tr>
<td>JAVA programs</td>
<td>Associates finite element grids to lump masses; combines force and pressure loads. General manipulation of the ASCII file representation of the FEA entities.</td>
</tr>
<tr>
<td>EXCEL spread sheets</td>
<td>Summarizes system weights and associates them with finite element grids; combines “unit loads” into flight loads.</td>
</tr>
<tr>
<td>EXCEL spread sheet-solver</td>
<td>Flight load balancing.</td>
</tr>
<tr>
<td>Text files</td>
<td>Lump mass processing; force and pressure processing.</td>
</tr>
</tbody>
</table>

3.1. Geometry and Finite Element Modeling

The initial estimates of vehicle weights and geometry have to be acquired from other sources such as the CONSIZE program. Appendix B is a listing of output from CONSIZE that contains a breakdown of system weights into multi-level sub-system weights. This output also contains
general design data and vehicle parameters with geometry information that serve as the starting point for the structural analysis.

Vehicle modeling is further divided into the following three interdependent tasks:

- Vehicle Geometry and Mass-less Finite Element Modeling Task,
- Vehicle Lump Mass Modeling Task,
- Vehicle Preliminary Stiffness Definition Task.

The final product of these three tasks is a vehicle finite element model built of mass-less shell elements and nodal lumped masses whose total weight equals the vehicle weight less the weight of main propellant. The user will notice the absence of other types of finite elements, such as beam elements, which one would expect to be present in the model beside stressed skin. The inclusion of beam elements is a complication to the procedure as it currently stands and is being worked as a future enhancement.

3.1.1. Vehicle Geometry and Mass-less Finite Element Modeling Task

In this task vehicle geometry is generated at the structural component sub-assembly level such as: fuel tank, vehicle nose, inter-tank assembly, payload bay, thrust structure, wing, tail and winglets. Those CAD surfaces are then meshed into finite element models of the sub-assemblies. The whole modeling process can be done either in a single I-DEAS Model file or in separate Model files.

At this stage of the modeling process, finite elements do not have mass and the stiffness is defined as for a 0.001 inch thick steel element with the following material properties: modulus of elasticity of $3 \times 10^7$ lb/in$^2$, Poisson’s ratio of 0.29 and mass density is 0.0 lb sec$^2$/in$^4$. Selection of steel and thickness was quite arbitrary.

The finite elements are then organized into groups of panels. Each shell finite element in the panel has the same physical property name assigned to it in I-DEAS. These panels are the smallest structural entities that may be later on analyzed and sized in HyperSizer. Panels represent distinct regions of a single set of manufacturing sizes. For example, a stiffened skin panel may be made up of many elements but each element will have the same stiffener arrangement and gage sizes as any other in the panel. In HyperSizer these panels are called "components". It is important that this process of associating the physical property names to the elements produces physically meaningful panels. Naming the physical properties and associating them with proper elements is therefore a very important step in the vehicle design process.

The user has three options to do vehicle geometry and mass-less finite element modeling tasks at the sub-assembly level in I-DEAS.

1. Create geometry and do meshing with the help of ready-made I-DEAS Program files.
2. Create geometry and mesh data using the I-DEAS Graphical User Interface (GUI).
3. Use available sub-assembly geometry models in so called I-DEAS "parametric form" and mesh them manually.
The first method is the simplest but least accurate one. The fuselage sub-structures are built of the simplest geometric entities such as cylinders, ellipsoids and frustum of cones. Figure 3 illustrates these sub-assemblies. Appendix C contains a typical I-DEAS Program file for a fuel tank that is used to generate geometry and finite elements for a liquid oxygen tank. The advantage of this method is that it is simple to apply. The disadvantage is that it does not cover more complicated shapes such as a droop nose.

This method can use an I-DEAS program for automated property assignment. This program is listed in Appendix D. The program runs interactively inside I-DEAS and requires the following information be provided by the user:

- Starting element number,
- Ending element number,
- Number of elements per property card,
- Property prefixes string.

The program assigns a physical property to the consecutive elements in the model. It allows further division of the sub-assembly with properties grouped around physically meaningful structural entities such as fuel tank bulkheads and barrels. It is well suited for simpler shapes such as fuel tanks, inter-tank adapters, simple nose sections and thrust structure. It should not be used for wing-like sub-assemblies and for complex shapes such as a droop nose.

![Figure 3a. Geometry of sub-assemblies generated by I-DEAS Program files](image)
Inter Tank Adapter

Thrust Structure

Figure 3b. Geometry of sub-assemblies generated by I-DEAS Program files

Payload Pod

Wing
Airfoil NACA 2408

LEGEND:
* Indicates Location and Dimension which may be controlled

Figure 3c. Geometry of sub-assemblies generated by I-DEAS Program files
The second option allows the user full capability of the IDEAS GUI environment. Geometry, meshing and property assignment data for individual parts must be completed. The rest of the process is general enough such that user defined components can be analyzed. A disadvantage to this method is that automation of man-in-loop process flow is not desirable.

The third method is sort of a mixture of the prior two. Prior part models of shapes more complex than have been used via the first method are stored in an IDEAS Library. These parts are retrieved with appropriate dimension values applied. A typical complex shape – droop nose section is shown in Figure 4 with variable geometric parameters shown in the figure. The library of so called I-DEAS “parametric models” could be generated ahead of time. One disadvantage of this method is that the Part Coordinate System may not be aligned with the I-DEAS Global Coordinate System and this may cause some problems in the ensuing steps if not taken care of (see Note in Figure 3a).

After all sub-assemblies have been created, they have to be assembled together into a vehicle assembly finite element model. Firstly, every sub-assembly model has to be exported from the I-DEAS Model File in Universal file format. The Universal files are then read into a new Model file one by one. Sub-assemblies generated from the parametric models should be imported last because of a problem with their coordinate system. This process will create new parts inside the Model file associated with each sub-assembly. Each part has also a finite element model associated with it. The FE models are separated and need to be assembled and appended into a vehicle assembly model. This process generates a few identical nodes at the interfaces between the parts. These nodes must be “equivalenced” (i.e. merged together) to provide structural continuity between the parts. Note that this assembly process was created in IDEAS V6. New code features, such as assembly FEA modeling in I-DEAS, may be taken advantage of as long as the intent of the process presented here is preserved.

![Transition section length](image)

_Nose length

_Droop angle

_Nose radius

_Figure 4. Droop nose geometry_
Connection between the wing and fuselage is modeled with Rigid Links or mass-less FE Beams with realistic stiffness properties. These elements will not be sized in HyperSizer and are in the model only to transfer load from the wing or tail surfaces into the fuselage. The detail of such a connection is shown in Figure 5. Care should be taken such that the rigid links tend to simulate physical connections that the joined parts would see in an actual assembly.

Figure 5. Rigid link or mass-less beam connection between wing and the fuselage

Finally, the model has to be prepared for preliminary vehicle weight definition and distribution. Densities of all materials in the model must be zeroed. Finite element nodes can be grouped into spatial groups which should correspond to the different vehicle systems listed in the CONSIZE output of Appendix B. The spatial grouping should be done so that the center of gravity of the group is as close as possible to the location of the center of gravity of particular system defined in CONSIZE output. The group names should be different from element property names.

The final product of this task is a vehicle finite element model with no mass and with arbitrary stiffness. Appearance of such a model is shown in Figure 6. This model has to be exported in I-DEAS Universal file format and will be used as an input file during the process of preliminary vehicle mass definition.
Figure 6. Finite element model of a launch vehicle

3.1.2. Vehicle Lump Mass Modeling Task

System weights from CONSIZE output (see Appendix B) have to be mapped to appropriate finite element grid points. This can be done in two steps. Firstly, weights are parsed either to the groups of grid points or to the region of grid points in the EXCEL spreadsheet. Text file format of such a spreadsheet is shown in Appendix E and the abbreviated form of that file is shown in Table 2. This file will be used as input into a JAVA program that maps the weights from CONSZ to IDEAS nodal masses.

Table 2. Abbreviated form of a CONSIZE_MOD Text file

<table>
<thead>
<tr>
<th>CONSIZ Component</th>
<th>FEA Group</th>
<th>Weight (lbs)</th>
<th>Mapping</th>
<th>X Begin (inch)</th>
<th>X END (inch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>begin_components</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>vert_fin</td>
<td>vertical_tail</td>
<td>4041</td>
<td>component</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>payload_bay</td>
<td>fuselage_side</td>
<td>6086</td>
<td>fofx</td>
<td>1574</td>
<td>1974</td>
</tr>
<tr>
<td>end_components</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
This spreadsheet/text file must begin with the statement “begin_components” in the first column and it must end with the statement “end_components” in the same column. Between these two statements, the user may establish the relationships between weights copied from the CONSIZE output and the finite element nodes. The first column also contains vehicle system CONSIZE names for a reference purpose only. Finite element model groups must be entered in the second column precisely the same way they were named in the model. There is one naming rule for the CONSIZE Component and the FEA Group:

- the CONSIZE Component should not be named the same as any finite element Physical Property Set data.

The “Weight” column contains the weights in pounds from CONSIZE. The user has two options to map the CONSIZE weight onto model nodes. The “component” entry in the “Mapping” column will allow the JAVA program to map, for example, 4041 lbs of vertical fin weight to all nodes contained in the FE group “vertical_tail”. Thus, the weight will be spread in form of lumped masses to all nodes of the particular group. The “fofx” entry will instruct the program to spread the weight only on the sub-set group of nodes which starts at location X-Begin inches in the I-DEAS Global Coordinates and ends at X-End. For example, the payload bay weight of 6086 lbs will be mapped between Station 1574 and Station 1974 on all nodes belonging to a group named the “fuselage_side”. Note that the nodal mapping is currently slightly inaccurate as mass will tend to concentrate where nodal density concentrates. Future versions of the process intend to use an areal spreading of the component masses and calculate nodal masses based on such a distribution.

Next, the user has to run the JAVA program “consiz2unv” to distribute vehicle weights according to the mapping plan set in the spreadsheet. This program requires two files as input: a text version of the EXCEL mass mapping data file, and a Universal file created from the current I-DEAS Model file. The output from this program is an I-DEAS Program file with vehicle masses lumped at model nodes. The last step in this task is to run the Program file inside I-DEAS to add the lumped masses to the model. Appendix F lists the JAVA code command to run the program. Parameter $1 of this input command is the name of the universal file, $2 is the mass mapping data file, and $3 is the name of a mass assignment program file that will be created.

The final product of this task is vehicle finite element model with all dry vehicle mass lumped at the nodes. The weight of the main fuel will be modeled as a time dependent pressure loading condition. A good check that all mass has been assigned to the I-DEAS finite element model is to check the model inertia properties in the I-DEAS Model file.

3.1.3. Preliminary Vehicle Stiffness Definition Task

At the end of this task all shell finite elements will have default stiffness properties assigned to them. The tasks consists of the following three steps.

Static analysis of the vehicle model exposed to an arbitrary load and restraint condition has to be done first in I-DEAS. This analysis may be “arbitrary” because HyperSizer will first be run in an
analysis (not sizing) mode to setup initial element stiffnesses. The goal of this analysis is only to create an I-DEAS model in Universal file format which is readable by HyperSizer. Application of loads and boundary conditions is irrelevant in the sense that the loading condition is unimportant to HyperSizer at this point but it is necessary to keep the Universal file in a format HyperSizer can deal with. The finite element model and results of this analysis should be in “Inch (pound f)” units. Before running the static solution analysis “Element Force” and “Shell Stress Resultant” should be selected as output results in I-DEAS. A Universal file with the model and the results is exported after the analysis.

Stiffness definition takes place in HyperSizer. The user is encouraged to read the HyperSizer Manual for detailed instructions on how to run the program in conjunction with I-DEAS finite element analysis. The procedure flow chart in Appendix A may be used as a guide for this particular process. The Universal file from the previous step has to be imported into the HyperSizer database. A vehicle material and a sandwich panel as a structural family need to be selected next. Note that HyperSizer offers a large selection of structural panel design concepts (i.e. families). For simplicity the current procedure uses only sandwich panels. This is an obvious limit of the procedure and can be overridden as the user gains expertise with HyperSizer and I-DEAS. All HyperSizer Components (where a Component is a group of shell finite elements with same physical properties in I-DEAS) need to be grouped into a single HyperSizer Group. The sandwich panel thickness of the Group needs to be defined. A default thickness of one inch is recommended (0.1 inch for the face sheets and 0.8 inch for the core). The Group variable (i.e. thickness) range should be set to a single value and permutation set to one. This is because there will not be a sizing run at this stage in the procedure. After setup of the HyperSizer model is complete and the program analysis option has been executed the properties and materials (i.e. stiffness and weights) of Components are exported by HyperSizer in I-DEAS Universal file format. Note that the I-DEAS Universal file output is generated only when the entire Project is analyzed.

Before reading the Universal file into a new I-DEAS Model file the consistent mass matrix of the shell elements has to be edited out. The updated vehicle FE model has preliminary stiffness defined for all mass-less shell elements, and all preliminary structural weights and system weights (with the exception of the main fuel weight) are modeled as lumped masses.

**3.2. External Load Modeling and Load Balancing**

The user must define a set of design load conditions that the vehicle model will be subject to. These load conditions may be such as: vehicle on the pad, liftoff, maximum dynamic pressure in flight, maximum thrust, main engine cut-off, re-entry and so on. Table 3 lists a set of load cases typically used for weight estimation. Information about these loads may be available to the user from different sources and programs.
Table 3. Design conditions

1) Proof  
2) 10 day wind on pad  
3) 1 day wind on pad  
4) liftoff  
5) Max Q  
6) Max Fn  
7) Max Axial acceleration  
8) Subsonic Entry Manever  
9) Main-Gear Touchdown  
10) All –Gear Touchdown  
11) Ground Handling

The procedure to create design loads is based on so called "Unit Load Sets" which are the simplest load building blocks of the design loads. Unit load sets are scaled, combined and balanced to create the actual design case loads listed in Table 3. The design loads are then used in the static analysis for element sizing. The process of creating design loads consists of several tasks (see Appendix A):  
- Generation of the Unit Load Sets,  
- Combination of the Unit Loads into flight loads and load balancing,  
- Processing of force and pressure loads,  
- Final assembly of loads into load conditions.

3.2.1. Unit Load Set Task

The most basic load sets are built in this task in I-DEAS. Their formulation and modeling is left to the user’s decision as long as the user is applying them consistently though the rest of the procedure. They may be defined as a unit pressure of 1 (psi) per element, as illustrated in Figure 7 for the “unit” wing lift, or as a unit force of 1 pound distributed to all thrust structure end bulkhead rim nodes. The Unit inertial loads are defined as properly oriented 1 G linear acceleration. The Unit rotational acceleration may also be defined. These load sets will be used whenever flight conditions require modeling of loads with variable magnitude.
Some loads may be modeled either as a unit load or they may be modeled with actual magnitude. Wind pressure on the vehicle on a launch pad is a load that often is modeled as a precalculated input surface pressure.

The fuel head pressure on the tank walls can not be modeled as a scaleable unit load. It must be modeled separately for each flight case. That is because it is a time dependent load due to the continual use of fuel and changing acceleration vector throughout the ascent trajectory. Figure 8 shows resulting pressure vectors on a tank wall as calculated for a typical fluid acceleration condition. Appendix G lists an I-DEAS Program file for automatically creating tank head pressure loads. Table 4 shows the input part of the same file with input lines that have to be edited by the user. Note 5 in Table 4 indicates that all tank finite elements must be grouped in the I-DEAS Model file in appropriate tank groups.

Figure 8. Tank head pressure
Table 4. Input lines from a tank head pressure modeling I-DEAS Program file

```plaintext
C : Start USER INPUT
C : position positive point on neg side to reverse pressure sign
K : /options global_symbols on
K : enter ldst_name
K : yes
K : "1h2_40%_2.93_0_0.17" This is a name of the load set as it will appear inside I-DEAS.
K : /options global_symbols on
K : enter grp_name
K : yes
K : "1h2_tank_elements" This is a shell elements group name which must be identical to the one previously defined in I-DEAS. See Note 5) below.

K : # ullage=.0
K : # rho_g=.0075042 See Note 3) below.
C : Vehicle acceleration
K : # ax=-2.93 See Note 2) below.
K : # ay=.0
K : # az=-0.17 See Note 2) below.
K : # declare pos(3)
K : # pos (1)=1441. See Note 1) below.
K : # pos (2)=.0
K : # pos (3)=.0
C : END USER INPUT
```

Following are the instructions how to organize input in that file.

1. Establish amount of fuel that remains in the tank and position of the fuel surface along the vehicle centerline in the Model Global Coordinate System.
2. Determine components of axial acceleration (i.e. along vehicle axis) and normal acceleration (i.e. Z axis of Figure 6). Express these components in unit gravitational acceleration (Gs).
3. Calculate magnitude of the resultant acceleration in Gs and multiply that number with fuel density in lb/in3.
4. Run the Program file.
5. Two head pressure regions will be generated. The first one is a “wetted” region which covers correct fuel tank elements below the fuel surface line (see Figure 8). The second region of elements is the erroneous one and it has to be graphically edited out in the I-DEAS Model file. This region is easily identifiable because the pressure arrows are directed in the opposite direction from those shown in the “wetted” region.

These Unit Load Sets are applied one at the time to the free-free FE model of the vehicle and static analyses are performed. I-DEAS Listing text files (.lis) and a Universal file (.unv) from these runs are saved for the next steps. The Listing files contain sum of applied loads and moments along the reference (Global) axes and the origin respectively (see Table 5).
Table 5. Unit Load run results in an I-DEAS Listing file

NET APPLIED LOAD FOR LOAD SET 6 - LH2 1PSI INTERNAL PRESSURE
FX = -3.61899D-11, FY = 4.60200D+05, FZ = -2.24052D-10
MX = -3.17788D-09, MY = -3.42105D-08, MZ = 4.22512D+08
MOMENTS TAKEN ABOUT THE ORIGIN

3.2.2 Combination of Unit Load Sets into Flight Loads and Load Balancing

This is the first stage during which the unit loads are combined and actual vehicle design load conditions are generated. All steps are done using an EXCEL spreadsheet. One spreadsheet per each load condition must be set. A typical load balancing spreadsheet is shown in Figure 9.

Resulting three forces and three moments from the Unit Loads analysis are copied to the respective Unit Load entry in the spreadsheet and scaled to physically meaningful magnitudes for a particular load condition (see Notes 2 and 3 in Figure 9). There is a list of more than twenty vehicle load sub-sets such as: lift, thrust, aero, nonstructural inertia loads, structural inertia loads, fuel loads etc. Some of the scaling factors can be predefined and are based on known load magnitudes during the vehicle flight stage or during vehicle ground operations on the launch pad. Input, such as vehicle acceleration, from other programs such as POST – a trajectory optimization program [4] may be used (see Appendix A). For unconstrained type flight conditions the other scaling factors must be calculated during the vehicle balancing process so that, applied normal forces, axial forces and pitching moments sum to zero (see Notes 4 and 6 in Figure 9). Therefore, these scaling factors, usually two to three, are treated as variables. This requires application of the EXCEL spreadsheet Solver (see Figure 9, Note 5). Solver is an optimization program which varies selected load scaling factors to achieve zero pitch moment subject to zero constraints on net axial and net normal force and subject to other constraints on flight loads. Outputs from the Solver are all computed scale factors. Constrained load conditions, such as having the vehicle exposed to wind on the launch pad, do not need to be balanced. All flight load conditions must be balanced.

Some flight load conditions, such as lift-off with impact considerations due to rapid thrust build-up and hold-down release may require special treatment. A simplistic calculation of a dynamic thrust factor for the liftoff condition is shown in Appendix H. Users may desire to calculate this effect with other methodologies. The liftoff acceleration must be multiplied by the dynamic magnification factor before being applied in the spreadsheet.
Information about the load case

Normal and axial net force and pitch moment copied from I-DEAS .lis file

Unit forces/ moment scaled by a magnitude factor

Accelerations, force or pressure

Figure 9a. Typical load balancing spreadsheet
Scaling factors for acceleration, thrust, lift etc.

Factors input by hand

Factors/design variables calculated by Solver

Objective function: Pitch moment = 0

Constraints on axial and normal force, and other flight constraints

Sum of balanced forces and moment

Figure 9b. Typical load balancing spreadsheet
3.2.3. Further Processing of Force and Pressure Loads

The goal of this task is to organize design load case data into a format readable by I-DEAS. The load scaling factors that were obtained in the EXCEL spreadsheets are applied to three distinct groups of loads. These loads are then combined together into I-DEAS load conditions. The three groups of loads are:

- Force loads
- Pressure loads
- Acceleration loads

Multiple force or pressure loads are combined into a single I-DEAS loadset with a utility computer program. The unit force (or pressure) loads are scaled and combined into force (or pressure) model flight loads by a JAVA program (see Appendix F for the program execution path). The program called “combine_loads” requires two input files: the I-DEAS Universal file which contains the Unit load definitions, and a text file which brings in information about scaling factors and defines which unit loads need to be processed. Listing of this text input file is shown in Table 6.

Table 6. An input file for the JAVA “combine_loads” program

<table>
<thead>
<tr>
<th>Name of I-DEAS .unv file with Unit loads</th>
<th>pressure This file will be used to combine pressure (force)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of Unit loads to combine</td>
<td>4</td>
</tr>
<tr>
<td>A new load set number defined for I-DEAS</td>
<td>liftoff combined pressure Name of a new load set in I-DEAS</td>
</tr>
<tr>
<td>Number and a scaling factor of a Unit load</td>
<td>6 10.3 7 22.0 17 1.36 21 1.36</td>
</tr>
</tbody>
</table>

The output from JAVA “combine_loads” is a new I-DEAS Universal file that consists of a single combined force (or pressure) loadset.

The Unit inertia (i.e. acceleration) loads have to be scaled in I-DEAS by the scale factors obtained in the EXCEL spreadsheets as appropriate for each final design load condition.

3.2.4. Final Assembly of Loads into Load Conditions

The three scaled load sets, i.e. the force, the pressure and the acceleration are then combined into the unified load condition in I-DEAS. This load condition is used in a Boundary Condition set and subsequently for a static solution set within I-DEAS so that the static analysis may be performed.
3.3. The First Static Analysis and Structural Sizing

The initial FE model of the launch vehicle will be subject to a number of static load conditions and preliminary internal running load distributions will be obtained at this stage. The internal loads will be used to perform the first structural sizing of the vehicle. A model of the newly sized vehicle, which has new stiffness and structural mass distribution, will be ready for a series of analysis-sizing iterations whose goal is to produce minimum structural weight design of the vehicle. This section deals only with the first in the series of analysis/sizing steps.

The process employs two commercially available softwares whose functions are coupled together. The static analysis is done as a natural continuation to modeling in the I-DEAS Model file. The structural element sizing is preformed in HyperSizer. The user is advised to become familiar with these two programs. Only general outline of program capabilities and specifics related to this procedure will be covered in this report.

3.3.1. The First Static Analysis

Analysis is done in I-DEAS. After the final load sets are generated, three more preparation steps are required. The Restraint Sets are built which define general boundary conditions of the vehicle such as: vehicle on the launch pad, landing gear and free-free boundary condition. The FE model does not have beam elements to model frames for concentrated load application to the model. Therefore, the user must carefully apply restraints, such as a nose gear restraint shown in Figure 10, to avoid application of concentrated loads normal to the plane of shell elements. Since only half of the model has been generated, symmetric boundary conditions must be modeled. Then, the Load Sets and Restraint sets are combined in the Boundary Conditions. Finally, a static analysis is selected in the Solution Sets.

There are two requirements imposed by HyperSizer on the IDEAS Universal file format:
- “Element Force” and “Shell Stress Resultant” outputs must be selected before running the FE analysis,
- the units must be changed to “Inch (pound f)”.

The model and the results should be exported into an I-DEAS Simulation Universal file after the static analysis.
3.3.2. The First Structural Sizing

HyperSizer integrates in a single tool structural design and analysis processes that are required to size a structure. Finite elements are grouped together into the smallest practically manufacturable pieces of structure called HyperSizer structural Components. Generally, Components may be either panel or beam concepts which can be analyzed and optimized subject to the imported running loads from I-DEAS and the pre-defined boundary conditions. Analyses include traditional industry methods and modern analytical and computational solutions. The optimization includes material selections and all of the dimensional variables such as panel and beam shapes, thicknesses, stiffening webs and flanges, spacings, and depths. The Components are organized into Groups that have the same initial input design parameters. Each Group belongs to a structural Family. Structural Families include broad definitions for panels and beams such as the “Unstiffened plate/sandwich family”, the “Corrugated stiffened family” etc. Within each Family there are several choices available which finalize the construction details of a concept.

The present launch vehicle structural design has utilized only the sandwich family with face sheets of equal thickness and of isotropic material. The current procedure does not support the use of other families or of beams. This is because there has not been an attempt to define material orientation vectors for stiffened skin panels in the I-DEAS-based part of the procedure, and because the beam finite elements are not generated in an automatic way and therefore are not available. All of the Groups are organized into a Project that contains all information about the structure including the finite element mesh and loads.
Following are the general steps for coupling FE analysis with HyperSizer.

- **Project Preparation** (create a Project, select the materials, setup project form).
- **FE Analysis Import** (import FE model, check and combine load sets).
- **Pre-Sizing Preparation** (select structural Family, assign FEM structural Components to Groups, select sizing variables and materials, build Assemblies, define panel buckling geometry).

After HyperSyzer analyses the Components of a Group, each will have unique design variables based as required upon Component loading and failure mode analysis. Groups can be reorganized at any time during the analysis if the initial grouping requires revision. Once the Groups have been established, each Component must be properly defined. This means the design variable ranges, material choice options, and failure mode options for each group must be input. Related to a panel based failure mode are panel length and width. These values will be read in directly from the input file, but it may be necessary to adjust the numbers to represent the stiffener direction or change in a span dimension assumed by the program. The honeycomb structural concept is used here for weight estimation purposes. Honeycomb is easy to work with in terms of structural analysis setup in HyperSizer and was sufficient to define data flow requirements. Future growth of this analysis procedure will incorporate the full sizing capability of HyperSizer.

- **Preliminary Sizing of a Component** (single analysis on a Component, import FEA running loads and review them).
- **Final Preparations** (select failure criteria and boundary conditions, select limits on variables, check loads, pressure and FEA computed moments).

Three Group design variable ranges must be defined, top face thickness, bottom face thickness, and core thickness. The user is advised to define the minimum gauge both for the face sheets and for the core. Selection of the minimum and maximum group variable bounds and the number of permutations may be guided by some industry standards. Proper selection of the variable bounds will ensure a minimum weight solution. Note that these bounds apply to the whole Group, which is an important consideration to have in mind when whole Project needs to be sized.

The user may adjust safety factors and failure modes. There are several factors in HyperSizer that may be set. By going into the “Design-to-Loads” tab the user can set a required margin of safety (MOS), a mechanical design limit load factor, and a mechanical design ultimate load factor. These settings are all very important when trying to simulate durability requirements.

- **Size and Iterate** (size Assembly/Group, check safety margins and limits on variables).

The recommended procedure is to size an Assembly first and check which Group has the Margins of Safety violated. This is an indication of an undersized structure. If a Group has minimum group variable bound reached, that is an indication of possible oversized structure. This requires that the variable bounds/permutations be adjusted.
• **Size the Project.**

After all of the setup of the HyperSizer model is completed and all Assemblies/Groups are sized, the properties and materials (i.e. stiffness and weights) of the optimized structural components are exported by HyperSizer in I-DEAS Universal file format. The I-DEAS Universal file output is generated only when the entire Project is sized. The user should check that the proper field [i.e. “FEM Properties and Materials Filename (created by HyperSizer)”] in the "Project Setup" form is filled up before sizing the Project.

### 3.4. Iteration between Static Analysis and Structural Sizing

The results of the first analysis and sizing are based on too many initial assumptions to be final. It is necessary to repeat the whole process to a satisfactory vehicle weight convergence and to a final vehicle design.

The iteration procedure is very similar to the first analysis and sizing process but there are also a few differences (see Appendix A).

A new I-DEAS Model file should be generated and the I-DEAS Universal file which was produced in the previous iteration need to be imported.

In the first iteration cycle only, the structural lumped masses which duplicate newly obtained shell/panel weight must be deleted from the I-DEAS Model file as obsolete.

If the variable bounds and permutations in HyperSizer were well posed during the first analysis and sizing cycle, then there will be only small changes of the bounds in the successive iterations.

### 4. Integration With Other Vehicle Analysis Tools

Upon successful structural weight estimation, the vehicle weight results may be passed back to the original codes (such as CONSIZE), from which they initiated, for update of input to these codes. Output from these codes, in form of vehicle geometry and new weight distribution and new external loads, will be a new input into the Structural Weight Estimation Procedure. This process may continue until there is satisfactory convergence of the vehicle design.

### 5. Conclusion

A process guide for utilization of 3D FEA and a commercial structural component design program in launch vehicle structural weight estimation has been presented. The guide is being presented at this time so users and developers of the technique have documented knowledge of the steps involved. There are indicated places in the procedure which currently are not highly rigorous, especially with regard to mass distribution, element property region assignment, and
airload distributions. This was done at the expense of having a more timely document. The document defines the analysis stages, data flow requirements, and presents them to those who will help implement the system in a more automated fashion. Current users of the process can be more exacting in specific areas at their own discretion, the general procedure should still be applicable. The process starts with a vehicle configuration and weight statement. It ends with a structural weight estimation based upon static strength analysis of a shell element representation of the vehicle. Such analysis capability provides weight sensitivity to structural arrangement, structural concept, material property, and design load variations. Because of complexity, the procedure is prone to user made mistakes. An effort to automate this process is underway and should reduce both the number of mistakes and the analysis time. Enhancements in the way of having more detailed finite element modeling and external load definition are also planned for the future.
6. References

Appendix A. Detail Outline of the Procedure for Structural Weight Estimation
EXTERNAL LOAD DEFINITION PHASE

1. Group Tank Elements
   - Generate Unit Load Sets I-DEAS

   Static Solution of Free-Free Vehicle under Unit Load Sets I-DEAS

   Combine Normal and axial Forces and Pitch Moments from Unit Loads into Flight Load Cases
   - EXCEL Spreadsheet .xls

   Add Flight Load Coefficients to the Unit Loads
   - EXCEL Spreadsheet .xls

   Balance the Loads in Flight Load Cases (FLC)
   - EXCEL Solver/Spreadsheet .xls

   Accel. scaling factors
   - Scaling factors

   Combine Force Loads in FLC Text Files
   - .txt

   Combine Pressure Loads in FLC Text Files
   - .txt

   Combine Force and Pressure Loads in FLC JAVA Program
   - .txt

   Generate Acceleration Loads I-DEAS

   Combine Force, Pressure and Acceleration into Flight Load Sets I-DEAS

2. Build Restraint Sets (Launch, Landing) I-DEAS
   - Define Boundary Conditions I-DEAS
   - Define Solution Sets I-DEAS

   Static Analysis with all Load Conditions I-DEAS
   - .unv

   Remove Pressure from .unv Text EDITOR
   - .unv

   Create a New Project HYPERSIZER

   Select Materials HYPERSIZER

   Setup Project Form HYPERSIZER

   Import FE Model HYPERSIZER

   Check/Combine Load Sets into Load Cases HYPERSIZER
Appendix B. Output from CONSIZE for WB004C Vehicle
### Weight Statement - Level III

#### Weight (lb) | Centers of Gravity (ft./ft.) | Mom. of Inertia (slug-ft x 10^-6)
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
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<tbody>
<tr>
<td><strong>LEVEL</strong></td>
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<td><strong>II</strong></td>
</tr>
<tr>
<td>----------------</td>
<td>-----------------------------</td>
<td>-----------------------------</td>
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<tr>
<td>1.0 Wing</td>
<td>24563.</td>
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<tr>
<td>Exposed wing surface</td>
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<td>Carry-through</td>
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<td>3.0 Body</td>
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<tr>
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<tr>
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<tr>
<td>LO2 tank</td>
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<tr>
<td>Structure</td>
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<tr>
<td>4.0 Induced environment protection</td>
<td>29901.</td>
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<td>Fuselage</td>
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<td>Running gear</td>
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<td>Control panel</td>
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<td>Alt</td>
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<td>8.0 Propulsion, orbital maneuver (OMS)</td>
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<td>Engines</td>
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<td>Propellant tanks</td>
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<td>Component</td>
<td>Initial Mass (kg)</td>
<td>Mass Change (kg)</td>
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<td>Propellant, orbital maneuver</td>
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<td>Accessories</td>
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<td>0.640</td>
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<td>Payload accommodations</td>
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<td>0.651</td>
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<td>Payload</td>
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<td>0.651</td>
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</table>

Total Initial Mass: 33,133 kg
Total Final Mass: 33,130 kg
100ml alt. circularization prop. 2330. 0.566 0.000 0.000 0.014 0.000 0.014
220ml alt. transfer/circ. prop. 10289. 0.566 0.000 0.000 0.062 0.000 0.062
Space station approach propellant 2392. 0.566 0.000 0.000 0.014 0.000 0.014
Deorbit propellant 9003. 0.566 0.000 0.000 0.054 0.000 0.054
PRELALATCH GROSS 2996427. 0.773 0.000 0.000 10.803 175.422 180.556
Prelaunch gross 2996427. 0.773 0.000 0.000 10.803 175.422 180.556
Start-up losses -3701. 0.780 0.000 0.000 -0.115 -1.829 -1.876
LH2 -4685. 0.335 0.000 0.000 -0.015 -0.057 -0.061
LO2 -32326. 0.844 0.000 0.000 -0.100 -0.073 -0.116
Gross lift-off 2989416. 0.773 0.000 0.000 10.687 173.590 178.777
Ascent propellant -2602362. 0.780 0.000 0.000 -8.098 128.604 131.932
LH2 -329459. 0.335 0.000 0.000 -1.048 -3.986 -4.289
LO2 -2272903. 0.844 0.000 0.000 -5.161 -8.186
Insertion (50X100 mi orbit) 357055. 0.720 0.000 0.000 2.589 43.217 45.075
Ascent reserves 79297. 0.780 0.000 0.000 0.000 -0.364 -0.364
LH2 1-103. 0.335 0.000 0.000 0.000 0.000 0.000
LO2 -6924. 0.844 0.000 0.000 0.000 0.000 0.000
OMS propellant - burn 1 2231. 0.566 0.000 0.000 -0.014 0.000 -0.014
Insertion (100 mi circular orbit) 346797. 0.720 0.000 0.000 2.575 42.719 44.564
Vented ascent propellant -10373. 0.668 0.000 0.000 -0.010 -0.008 -0.008
OMS propellant - burns 2 & 3 -10289. 0.566 0.000 0.000 -0.062 0.000 -0.062
Insertion (220 mi circular orbit) 326336. 0.727 0.000 0.000 2.503 42.252 44.035
CEP propellant - station approach -2392. 0.566 0.000 0.000 -0.014 0.000 -0.014
RCS propellant -3000. 0.566 0.000 0.000 -0.009 -0.336 -0.345
Payload delivered -25000. 0.651 0.000 0.000 0.000 0.000 0.000
Payload accepted 25000. 0.651 0.000 0.000 0.000 0.000 0.000
Fuel cell reactants -1612. 0.566 0.000 0.000 0.000 0.000 0.000
Evaporator water supply -2427. 0.088 0.000 0.000 0.000 0.000 0.000
Helium supply -136. 0.903 0.000 0.000 0.000 0.000 0.000
OMS propellant - deorbit -9003. 0.566 0.000 0.000 -0.054 0.000 -0.054
Entry 307566. 0.740 0.000 0.000 2.426 39.573 41.273
RCS prop. (entry) -988. 0.566 0.000 0.000 -0.003 -0.111 -0.114
Buoyancy -8480. 0.488 0.000 0.000 -0.025 -0.950 -0.975
Landed 298989. 0.748 0.000 0.000 2.397 37.573 39.250
Payload (returned) -25000. 0.651 0.000 0.000 -0.023 -0.069 -0.069
Landed (p/l out) 273989. 0.757 0.000 0.000 2.374 37.094 38.772
Payload accommodations 0. 0.651 0.000 0.000 0.000 0.000 0.000
Personnel 0. 0.000 0.000 0.000 0.000 0.000 0.000
Crew & gear 0. 0.640 0.000 0.200 0.000 0.000 0.000
Accessories 0. 0.640 0.000 0.200 0.000 0.000 0.000
Main prop. sys. pressurant -3211. 0.668 0.000 0.000 -0.003 -0.003 -0.003
Subsystem residuals -858. 0.088 0.000 0.000 0.000 0.000 0.000
Aux. propulsion residuals -2128. 0.566 0.000 0.000 -0.009 -0.183 -0.189
CEP and RCS -2228. 0.566 0.000 0.000 -0.009 -0.183 -0.189
Aux. propulsion reserves -2000. 0.566 0.000 0.000 -0.009 -0.124 -0.132
CPE -896. 0.566 0.000 0.000 -0.005 0.000 0.000
RCS -1104. 0.566 0.000 0.000 -0.003 -0.124 -0.127
Buoyancy 8480. 0.488 0.000 0.000 0.025 0.950 0.975
Empty w/growth 273081. 0.754 0.000 0.000 2.379 37.817 39.506
Landed - RTLS abort (max. p/l) 325274. 0.000 0.000 0.000 0.000 0.000 0.000

* INDICATES WEIGHT IS NOT WITHIN LIMITS OF WEIGHT EQUATION

wb-004c, gr-ep lh2, ws-2100 - 25 klb p/l, 51.6 deg incl.

DESIGN DATA

growth allowance fraction 0.1500
payload weight (lb) 25000.0000
additional down-payload (lb.) 25000.0000
payload bay diameter (ft.) 15.0000
payload bay length (ft.) 35.0000
payload volume (cu. ft.) 6185.0000
mission duration (days), max. 9.0000
one delta v for tank sizing (ft./sec.) 1100.0000
one delta v (ft./sec.) - burn 1 91.0000

34
| Mass ratio | 8.2884 |
| Propellant mass fraction | 0.8793 |
| Body length (ft.) | 227.2 |
| Wing span (ft.) | 112.9 |
| Theoretical wing area (sq. ft.) | 5099.9 |
| Wing loading at design wt (psf) | 63.8 |
| Wing planform ratio, span/chord | 0.58 |
| Sensitivity of volume to burnout wt (cu. ft./lb.) | 463.2 |
| Burnout weight growth factor (lb/lb) | 3.3 |

### BODY

| Total volume (cu. ft.) | 169251.0 |
| Task volume (cu. ft.) | 111677.0 |
| Fixed volume (cu. ft.) | 0.0 |
| Tank efficiency factor | 0.6637 |
| Ullage volume fraction | 0.0300 |

### DENSITY

<table>
<thead>
<tr>
<th>PROPELLANT FRACTION</th>
<th>DENSITY (lb/cu. ft.)</th>
<th>FLUID VOLUME (cu. ft.)</th>
<th>TANK VOLUME (cu. ft.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>lH2</td>
<td>0.1266</td>
<td>4.42</td>
<td>75825.0</td>
</tr>
<tr>
<td>lO2</td>
<td>0.8734</td>
<td>71.14</td>
<td>32501.0</td>
</tr>
<tr>
<td>lO2 (Wing)</td>
<td>0.0000</td>
<td>71.14</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Appendix C. I-DEAS, Version 6, Program File for Generation of Geometry and Finite Element Meshing of Fuel Tanks
C : units preference
K : $ return
K : $ mpos ;; /0 U U
K : inch
AP: 1 8 Change View
AP: 1 0 0 0 0
AP: 0.0 0.0 0.0
AP: 1.000000 0.0 0.0
AP: 0.0 1.000000 0.0
AP: 0.0 0.0 1.000000
AP: 0.1250000 0.2520000 0.2520000 15.000000
AP: -1.000000 -1.000000 -1.000000
AP: 1.000000 1.000000 1.000000
C : setup variables
C : use global symbol for component name
K : /options global_symbols on
K : enter comp_name
K : "lox tank"
C :
K : #x_offset=424.515
K : #x_rotation=90.
K : #rl=191.84
K : #ecc1=sqrt(2)/2.
K : #barrel_len=987.168
K : #rl2=191.84
K : #ecc2=sqrt(2)/2.
K : $ return
C : from lox_tank_zx.prg
C : below is born.prg type file
K : $ return
C : local switch off
K : $ /w gl:
K : $ mpos ;; /ma na
K : LAB
K :
K : B
K : main
K : n
K : comp_name
K : ok
K : done
K : $ return
K : $ /cr ref cs
K : LAB
K : comp_name
K : cs
K : cs2
K :
K : tra
K : x_offset .0 .0
K : rot
K : x_rotation .0 .0
K : done
C : attach to part, coord system, plane
K : $ /w at
K : LAB
K : comp_name
K : coordinate
K : cs3
K : xy_plane
K: $ mpos ;; /v wp
K: $ return
C: create fwd ellipse
K: $ /cr el co
K: OP
K: FX -r1*ecc1
K: FY .0
K: SX .0
K: SY r1
K: TX -r1*.5
K: TY r1*.707
K: RO .41
K: OKAY
P:
K: $ return
C: create aft ellipse
K: $ /cr el co
K: OP
K: FX barrel_len+r2*ecc2
K: FY 0
K: SX barrel_len
K: SY r2
K: TX barrel_len+r2*.5
K: TY r2*ecc2
K: RO .41
K: OKAY
C: Create tangent line to tops of fwd and aft domes
K: $ return
K: $ /cr 1 si
K: OP
K: PX .0 FY r1
K: SX barrel_len SY r2
K: OKAY
K: $ return
K: $ /cr se
K: OP
K: AU
K: Y
K: ST
K: N
K: Okay
K: LAB
K: comp_name
K: curve
K: 2
K: done
K: RE
K: label
K: comp_name
K: section
K: 1
K: KEY
K: 10 0 0
K: angle
K: -180
K: ok
K: $ return
P: start simulation
K: $ $ $ /ta xx SI
K: $ $ $ /ta MB
C: start groups
K : $ mpos ; ; /GR IP DI
K : P
K : fem_one
K : ok
K : $ return
K : /
K : group create
K : label
K :
K : surface
K : join5
K : 3
K : done
K : fwd_dome
K : /gr cr
K : label
K :
K : surface
K : join5
K : 2
K : done
K : barrel
K : /gr
K : cr
K : label
K :
K : surface
K : join5
K : 1
K : done
K : aft_dome
C : mesh aft dome
K : DFN
K : SH
K : LAB
K :
K : 5
K : 1
K : done
K : MT
K : MA
K : MO
K : DC
K : LAB
K :
K : 5
K : 1
K : DFE
K : 10
K : set
K :
K :
K : !
K : !
K : !
K : 20
K : done
K : E
K :
K : 5
K : *
K: 5
K: 1
K:
K:
K: $DEL
K:
K: S
K: *
K: C
K: S
K: vie rei; don
K: DFE
K: !
K: PU
K:
K:
K:
K: $DEL
K: DFE
K: !
K: Cancel
K: PM
K: PM
K: OK
C: from domemesh file worked ok
C: aft dome
K: define
K: SH
K: label
K:
K: joinS
K: 1
K: done
K: MT MA
K: MO
K: DC
K: LAB
K:
K: 5
K: 1
K: DFE
K: 10
K:
K: 10
K:
K: Cancel
K: PM
K: OK
C: barrel
K: define
K: sh
K: label
K:
K: joinS
K: 2
K: done
K: MT MA
K: MO
K : DFE
K : 12
K :
K : 10
K : CANC
K : PM
K : OKAY
C : fwd dome
K : define
K : sh
K : label
K :
K : joinS
K : 3
K : done
K : MT MA
K : MO
K : DC
K : LAB
K :
K : 5
K : 6
K : DFE
C : was S
K : 10
K :
K : CANC
K : PM
K : OKAY
C :
K : /group
K : set_current
K : fwd dome
K : Display_group
C : used to add entities to a group in this case
C : related elements added to a surface
K : /group
K : set_current
C : (variable) name of group
K : aft dome
K : Display_group
K : add
K : related_to
K : ELEM
K : LAB
K :
K : label
K : filter
K : pickable_menu
K : 3
K : done
K : pick_only
K :
K : surface
K : joinS
C : (variable) surface label to add elements to
K : 1
K : done
K : done
K : DG
C : used to add entities to a group in this case
C: related elements added to a surface
K: /group
K: set_current
C: (variable) name of group
K: fwd_dome
K: Display_group
K: add
K: related_to
K: ELEM
K: LAB
K:
K: label
K: filter
K: pickable_menu
K: 3
K: done
K: pick_only
K:
K: surface
K: join5
C: (variable) surface label to add elements to
K: 3
K: done
K: done
K: DG
C: used to add entities to a group in this case
C: related elements added to a surface
K: /group
K: set_current
C: (variable) name of group
K: barrel
K: Display_group
K: add
K: related_to
K: ELEM
K: LAB
K:
K: label
K: filter
K: pickable_menu
K: 3
K: done
K: pick_only
K:
K: surface
K: join5
C: (variable) surface label to add elements to
K: 2
K: done
K: done
K: DG
Appendix D. Listing of I-DEAS Finite Element Property Assignment Program

C : Zoran's Program for property assignment
K : # elno=1
K : # elmax=1
K : # nth=5
K : # tinc=.00
K : # thk=.001
K : # prefix=""
K : #input "starting element no. =>" elno
K : #input "ending element no. =>" elmax
K : #input "how many elements per property car =>" nth
K : # nthmax=nth+1
K : #input "property prefix string =>" prefix
C : #input "starting thickness minus .001 =>" thk
C : First property setup
K : # if (0 EQ 0) then; ,
K : # pname=prefix+elno; ,
K : # thk=thk+tinc; ,
K : # iter=0
K : /ph cr; ,
C : cr; ,
K : tn; ,
K : pname; ,
K : no; ,
K : tk; ,
K : thk; thk; thk; thk; ,
K : done
K : DES
C : first pause
C : Loop over all elements
K : # loop1:
K : # iter=iter+1
K : # output "iter is " iter
C : New property if at right increment
K : # if (iter GT nth) then; ,
K : # pname=prefix+elno; ,
K : # thk=thk+tinc; ,
K : # iter=1; ,
K : /ph cr; ,
K : thin_shell; ,
K : pname; ,
K : no; ,
K : tk; ,
K : thk thk thk thk; ,
K : done
K : DES
C :
K : /element
K : modify
K : label
K : elno
C : # ON_ERROR IGNORE
C : # ON_ERROR GOTO skipl
K : done
K : P
K : # pname
K : yes
K : # output "elno prop modified"
K : # skipl:
K : # elno=elno+1
K : # if (elno LE elmax) then #GOTO loop1
E : **** END OF SESSION ****
Appendix E. Listing of CONSIZE_MOD.txt file

From I:\Zoran\VAB\Son of HAVOC\wb004c.xls

WEIGHT STATEMENT - LEVEL III
wb004c external "p/l," ssme block2 -

CONSIZ_Component FEA_GROUP Weight Mapping XB XE

begin_components
wing_exposed wing_exposed 18448 component 0 0
wing_carrythru wing_carrythru 3599 component 0 0
wing_fairing wing_fairing 2516 component 0 0
vert_fin vertical_tail 4041 component 0 0
nose_assy nose_assy 2683 component 0 0
LOX_Tank lox_Tank 15100 component 0 0
intertank_assy intertank_assy 8032 component 0 0
LH2_Tank lh2_Tank 21047 component 0 0
payload_bay fuselage_side 6086 fofx 1574 1974
thrust_str thrust_str 8608 component 0 0
aft_bd_fairing aft_bd_fairing 1988 component 0 0
base_closeout base_closeout 600 component 0 0
body_flap Assy body_flap Assy 2199 component 0 0
tps_fuselage nose_fus_thrust 18483 component 0 0
tps_wing_fin tps_wing_fin 9431 component 0 0
insulation_nose nose_assy 233 component 0 0
insulation_pl_door fuselage_top 121 fofx 1574 1974
purge_vent_drain fuselage_side 983 fofx 500 2730
baleTast nose_assy 3328 fofx 0 180
growth_conting nose_fus_thrust 35658 component 0 0
end_components

empty 237724 338716 100992
sum 357057 536281 179224 ok
Appendix F. Listing of Commands to run JAVA Programs

# alias consiz2unv java -classpath ~/javacode/public consiz2unv junk.unv tsto_consiz.in.txt masses.prg
alias consiz2unv java -classpath /cerro/javacode/public consiz2unv $1 $2 $3

# java -classpath /cerro/javacode/public:. combine_loadsets input_filename output_unvfile_name
alias combine_loadsets java -classpath /cerro/javacode/public:. combine_loadsets $1 $2
Appendix G. Typical Tank Head Pressure I-DEAS V6 Program File

C : Start USER INPUT
C : position positive point on neg side to reverse pressure sign
K : /options global_symbols on
K : enter ldst_name
K : yes
K : "lh2 40% 2.93 0 0.17"
K : /options global_symbols on
K : enter grp_name
K : yes
K : "lh2_tank_elements"
K : # ullage=.0
K : # rho_g=.0075042
C : Vehicle acceleration
K : # ax=-2.93
K : # ay=.0
K : # az=-0.17
K : # declare pos(3)
K : # pos(1)=1441.
K : # pos(2)=.0
K : # pos(3)=.0
C : END USER INPUT

C :
K : # declare pos2(3)
K : # pos2(1)=pos(1)-100.
K : # pos2(2)=pos(2)
K : # pos2(3)=pos(3)
K : # ax=-ax
K : # ay=-ay
K : # az=-az
K : $ return
K : $ mpos ;; /O P
K : P 1;
K : ME ON
K : OKAY
K : P 2;
K : FD OF
K : OKAY
K : OKAY
K : OKAY
K : $ return
K : /ta bo
K : SE
K : ST
K : LOAD
K : SE
K : ldst_name
K : CR
K : make_current
K : Cancel
K : CR
K : AD
K : H
K : UG
K : directory
C : next
C : backup
K : grp_name
K : done
K : POI
K : KEY
K : ax ay az
K : KEY
K : pos
K : KEY
K : pos2
K : ullage
K : rho_g
K : $ return
K : $ mpos ;/O P
K : U
K : Y
K : Okay
K : $ return
Appendix H. Calculation of Dynamic Thrust Factor for Liftoff Condition
Based on Dutch Mayer’s Internal Memo

List of Symbols:
\( W \) = Vehicle weight at liftoff
\( T_a \) = Axial component of the thrust force at liftoff
\( T_n \) = Normal component of the thrust force at liftoff

Before engines are started, the weight \( W \) of the vehicle is supported solely at the eight tiedown mounts. Figure G1 is a simplified cartoon representation of the vehicle that shows only one tie-down mount on the bottom left of the vehicle and one engine mount on the right. There are actually six engine mounts in the full vehicle.

Define thrust to weight ratios: \( T_a / W = t_a \), and \( T_n / W = t_n \). Then \( T_a = t_a W \), and \( T_n = t_n W \).

![Figure G1](image)

**Figure G1. Free Body Diagram of a Launch Vehicle During Liftoff**

The engines are then lit, and supply \( t_a W \) axial thrust and \( t_n W \) normal thrust at the engine mount. The second free body diagram in Figure G1 shows the “quasi” static condition. The \( t_a W \) axial thrust is supported by the weight \( W \) of the vehicle and a reaction \((t_a-1)W\) at the tie-downs. The transverse thrust \( t_n W \) is supported solely at the eight tie-down mounts.

Finally, the tie-down bolts are released and the reaction forces “spring back”. Because of this dynamic phenomena, there is now \((t_a-1)W + t_a W = (2t_a-1)W\) axial thrust and \(2t_n W\) normal thrust. This equals to a \((2t_a-1)W/(t_a W) = 2-(1/t_a)\) axial dynamic factor, and \(2t_n W/(t_n W) = 2\) normal dynamic factor.
**Title and Subtitle:**
A Procedure for Structural Weight Estimation of Single Stage to Orbit Launch Vehicles (Interim User's Manual)

**Authors:**
Zoran N. Martinovic and Jeffrey A. Cerro

**Performing Organization:**
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**Abstract:**
This is an interim user's manual for current procedures used in the Vehicle Analysis Branch at NASA Langley Research Center, Hampton, Virginia, for launch vehicle structural subsystem weight estimation based on finite element modeling and structural analysis. The process is intended to complement traditional methods of conceptual and early preliminary structural design such as the application of empirical weight estimation or application of classical engineering design equations and criteria on one dimensional "line" models. Functions of two commercially available software codes are coupled together. Vehicle modeling and analysis are done using SDRC/I-DEAS, and structural sizing is performed with the Collier Research Corp. HyperSizer program.

**Subject Terms:**
Weight Estimation, Structural Design, Structural Sizing, Reusable Launch Vehicle Design, Finite Element Modeling

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