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MASS PROPERTIES REPORTING

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#1:SAWE Paper No. ZZZZ Statistical Mass Properties Predictions for a Program.

**Introduction:**

You receive the following Program Office Request: In lieu of mission specific analysis, it is dictated to you that Class Analysis be instituted to lower overall program cost. There may be other methods to address this request but this paper addresses one process that provided mass properties in support of program “Class Analysis”. To get started, a definition of Class Analysis is prudent. Class Analysis is any single study that incorporates all conceived configurations of a vehicle from mass properties perspective and the uncertainties associated with them.

The main purpose is to provide a range of mass properties with a high likelihood that the current and future fleet elements will not exceed them.

This process is based on simulated aerospace hardware data and does not reflect any specific line of vehicles. Additionally, the same process may be applied to non-aerospace production programs. All that is required is a good history of launch vehicle segments along with mass properties and uncertainties for each segment. Ten (10) years of history is ideal, but a smaller term is acceptable knowing that risk may be incurred. A segment is defined as any portion of the launch vehicle that may get jettisoned during the launch cycle. A robust verification process to validate that the assumed variables are still compliant is also a must.

This analysis will not only be performed by the mass properties group but also by all the downstream users (Guidance, Flight Mechanics, Separation, Structures, Ground Ops …etc.). Mass Properties is the initial cog in a long string of analysis that will be scrutinized. This being said, the mass properties group must not operate in a vacuum, but coordinate with these downstream users to access the effects of your assumptions. All data units herein will be presented as: Mass (M) = pounds-mass (lbm); Center of Mass (CM) = inches (in) or stations; and Moment and Product of Inertias (MOI and POI) = slug-foot2 (sl-ft2). Inertias will be in respect to the CM. A positive integral definition will be used for POI

**History**

Typically, for any mission analysis, mass properties and uncertainties are provided for each vehicle segment. There could be up to four (4) cycles for each mission:

1. Trajectory Design (TD)
2. Preliminary Analysis (PA)
3. Final Analysis (FA)
4. Tested and Guaranteed Data (TAG)

The TD will not be addresses herein due to its low likelihood of being performed. The PA may not be performed for repeat missions leaving the FA and TAG cycles to be performed for each mission. TAG (Tested and Guaranteed) refers to the verified (weighed) components. The above analyses are time-phased across the contract period. Note that your cycles and milestones may be named and phased differently.

At each of the above analysis milestones, the mass properties (MP) and uncertainties (Uncert.) is provided. The results of these analyses are provided to the downstream users (Guidance, Flight Mechanics, Structures, Ground Operations, and Independent Evaluators).

At typical dataset for a vehicle segment would resemble the data presented in Table 1. There could be numerious segments associated with any mission (e.g. 1st Stage, 2nd Stage, 3rd Stage, Fairing, Adaptors and Boost Motors)

**Table 1**



The mass uncertainties may be derived from either of two (2) methods.

**Method 1:** Using Detail Parts Database

The 1st method uses a mass growth depletion table (see Table 2) as a basis. Growth is not used herein, but the same data set of variables is used to determine uncertainties by the root, sum, squared (RSS) method to each of the detail parts within the database (see Example 1). Unique to this Growth Depletion Schedule (Table 2) is that variables exist for the “Actual” items (Material Codes 7 & 8). Most growth depletion schedules use zero (0%) for these items. The rational to use small percentages is that verified items still have uncertainties associated with them. The small % will not impact growth significantly if you are tracking growth.

**Table 2**

**Typical Mass Growth Depletion Schedule Example**



**Example 1**

**Developing Mass Uncertainties Using Growth Depletion Table as a Basis**



**Method 2:** Using End Item Mass Historical Data

This method incorporates mass uncertainties developed by using historical data. The equation used was previously identified in SAWE Paper #ZZZZ (see Reference #1, Equations #4 & #5).

 **Eqt #4:** (STDEV(Prelim (or Final)) % diff. (array)) \* 3 = standard deviation (±%)

 (3 sigma)

And

 **Eqt #5:** $\sqrt{(Eqt \#2 (mass accuracy)) \^2 + (Eqt \#4 )\^}2$ = mass uncert. (±%)

 (3 sigma)

The equations may be applied to Table 3 Expanded Mass Tracking History, and use the mass uncertainties data (PA & FA).

**Table 3(1)**

**Expanded Mass Tracking Example**



The resultant data is calculated as follows:

**Eqt #2:** PA Mass Uncertainty Example:

=average(Prelim(array)) + PA Bias ± =average(Prelim(array)) + PA Bias x PA Mass Uncert.

 (60,930 + (60,930 x -0.40%)) = 60,688; ± (60,688 x ±1.40%) =60,688 ±850 lbm

**Eqt #3:** FA Mass Uncertainty Example:

=average(Final(array)) +FA Bias ± =average(Final(array)) + FA Bias x FA Mass Uncert.

 (60,597 + (60,597 x -0.21%)) = 60,471; ± (60,471 x ±1.34%) =60,471 ±808 lbm

**Investigation:**

This paper will restrict its examples to mass only. The same process may be used for each mass properties element. This will eliminate many redundant charts and examples.

The key to this analysis is symmetrical uncertainties. Asymmetrical uncertainties could be used but are not addressed herein. Table 4 provides a historical example of a fleet element mass and uncertainties.

**Table 4**

**Mass Tracking Example(1)**



The early assumption was to plot the maximum and minimum mass values for each PA mission (above Items 1 through 8). Note that Missions “D”, “F” and “H” do not have any corresponding mass values whereas the FA and TA do. This was done to provide an example of a possible repeat mission which does not require PA data. Figure 1 provides an illustration of the plotting PA maximum and minimum mass results.

 

**Figure 1**

To cover all potential points, it was felt prudent to include all other data points (PA and FA) because of their availability. Figure 2 presents the plotting results which include maximum and minimum PA and FA data.



**Figure 2**

Note that some of the FA data points (Mission B and possibly D) created new minimum values. If you look at the raw data, note that the nominal mass values decrease for Mission B and the uncertainties also decrease. The resultant minimum mass value is smaller than the PA minimum result. Mission D does not have a minimum PA value.

Finally, the TAG values are included. The resultant eye-chart is presented in Figure 3.



**Figure 3**

All data from Table 4 has been accounted for. All TAG data fall within expected parameters. Note that certain trends (Missions “A”, “B” and “C” vs the rest of the fleet) exists and offer unique opportunities to be addressed.

**“The Fix”**

It was previously stated that the goal is to provide a set of mass properties that cover the total configuration (Class) of fleet elements. Figure 3 identifies all historical minimum and maximum values. We will now address creating boundary limits that other technologies can now work to. Where we are providing generic boundaries, rounding up or down will be to whole units. Two implementation solutions using uncertainties will be addressed (Solution 1 & 2). Solution 3 will use nominal data and the newly calculated 3 sigma uncertainties.

Solution 1: Include the entire database (Figure 3) and provide one singular solution. See Figure 4.



**Figure 4**

The above solution results in a nominal value of 61,000 ±2,250 lbm to use for all future analysis. This conservative estimate establishes new upper and lower limits going forward.

Solution 2: To address an identified opportunity, segregate early missions and provide limits based on current data. See Figure 5 where Missions “A”, “B” and “C” are excluded from the final results.



**Figure 5**

The above solution results in a nominal value of 60,250 ±1,500 lbm to use for all future analysis. This estimate ignores the early missions and establishes new upper and lower limits based on current data.

Solution 3: Use Historical data to provide statistical parameters. Method 2 identifies the process. It is recommended that these values be rounded up (or down) to the nearest whole numbers. To quote my mentor, Bob Knapp, “we do not want to provide highly precise inaccurate data”. Figure 6 provides nominal PA, FA and TAG data and the resulting limits.



**Figure 6**

The above data is derived from the Table 3 PA data (Eqt #3) with the maximum and minimum values rounded to 60,700 ±1,000 lbm.

Either method (Solution 1, 2 or 3) is acceptable. A summary of the three (3) solutions is as follows:

 Solution Nominal Uncert. Max Mass Min Mass Units

 1 61,000 ±2,250 63,250 58,750 lbm

 2 60,250 ±1,500 61,750 58,750 lbm

 3\* 60,700 ±1,000 61,700 59,700 lbm

Note \*: If Missions A, B and C were eliminated (similar to Solution 2), the results would be less restrictive.

A purist statistician would lean toward Solution 1 or 3 which includes all data. An engineer who is knowledgeable with the hardware may lean toward Solution 2 because he may know that the first three (3) missions flew unique configurations which may never fly again and that due to limited data, the resultant mass bias and uncertainties were large due to lack of knowledge.

Note that Solution 3 is only applicable to mass property items that have been verified. Example: the verification method uses a two (2) point lift process resulting in the verification of mass and one Center of Mass (CM) item. The remaining CM and Inertia items have not been verified. You have the option to mix and match all three solutions to provide complete mass properties parameters. It’s up to you.

**Implementation:**

Mass (M)

As previously addressed, Solution 3 would provide unique 3 sigma parameters for mass. Most programs tract and verify mass. Normally, historical data should be available on most programs. Simply, it’s the statistical difference between the predictions and the verified mass. One may also use this process at the detail part level to establish detail part uncertainties.

Center of Mass (CM)

The CM may use a mixture of Solutions; 1, 2 or 3. Rounding of values will be driven by the product line but normally limited to two (2) decimal points.

Inertias (MOI & POI)

Unless your product line is spacecraft oriented, rarely are the Inertias verified. That would leave Solutions 1 & 2 to help quantify your maximum and minimum limits.

Before casting your final results in concrete, it is highly recommended that the results be coordinated with the downstream users. If some downstream users are negatively impacted by these results, you may be forced to use less conservative analysis for some of the MP items.

**Considerations:**

The incorporation of this concept was unique to a specific product line. Tailoring may be advised for different product lines. Some items to consider are listed below:

1. Start off conservatively (Solution 1). You can always back-off if any of the downstream users are negatively impacted.
2. If any of the MP limits are still not acceptable after downstream coordination with the users, the Program Office must be notified. The ultimate solution may be to keep verifying (weighing) this item.

Example: You provide the mass limits of 61,000 ±2,225 lbm (or ±3.65% from Solution 1). Your Shipping Department cannot live with that dispersion. You can then provide Solutions 2 or 3 results. If they still cannot live with the results, the last resort remedy (costly) would be to weigh each element which could reduce the dispersion from ±3.65% to approximately ±0.25%. The Program Office will have to cost in this verification activity to meet the Shipping Department’s needs. If Solution 1, 2 or 3 still does not meet the Shipping Department’s needs, find a new Shipping Department. This organization may be putting all of the risks on you to minimize their Class Analysis effort.

1. For any young program, a major issue will be the lack of data points for statistical analysis. There are statistical tools out there that can be used for analysis using small number of data points. No recommendations are made herein.
2. Another use of the data would be to create historical Class Uncertainties for each segment. The nominal data would vary but the uncertainties would remain the same. See Appendix B, Table 6 for a historical uncertainties presentation.
3. Start looking for a new position. Class analysis is designed to reduce overall program cost. This reduction is to simplify the analysis which in turn may eliminate the analyst tasks across the engineering board. As defined in this paper’s title, “a.k.a. MP End of Times” , positions are being reduced.
4. It is recommended that a senior analyst be chosen to perform this task. A senior engineer understands the Program Office requirements to remain competitive and profitable and may have gone through staff reduction exercises previously. He/she may not be spending excessive time looking for new career positions.

**Conclusions/Recommendations:**

The basis for mass properties Class analysis is a current database, a robust verification process and a good history of the data being evaluated. You can never get enough data points in support of your analysis. Even when equilibrium between predicted and verified elements are reasonable, periodic verification is highly recommended just to ensure that the process is still viable.

Do not excess your weighing/verification equipment.

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| **Appendix A****Table 5****Mass Bias and Uncertainties History Example****Figure 7****Ideal Historical Chart Example****Appendix B****Table 6(1)****Segment Uncertainties Example****Appendix C****Acronym Listing** |  |  |  |  |  |  |