The Impact of Rapid Structural Analysis in the Configuration Development of 2^{nd} and 3^{rd} Generation Launch Vehicles

Abstract

The process by which aerospace vehicles are developed consists of analyses at levels of fidelity that increase as the configuration becomes better defined. Early in the development, configuration definition is driven primarily by aerodynamic factors like performance and stability, with highly simplified models of the structural aspects of the vehicle, often in the form of parametric weight equations. It is only after further development, when a single primary configuration has been selected, that a finite element model is typically constructed for structural analysis. Its most obvious output is a more accurate estimate of structural weight, but another important benefit of this analysis is the identification of structural show stoppers. With conventional configurations such as subsonic aircraft of the body and wing type, a large body of experience guides designers away from infeasible configurations. However, with innovative and unconventional designs like those for reusable launch vehicles, analytical detection of problems is important.

The barrier to early application of accurate analysis has been the cycle time for the sizing of a structural model, often as long as six months to a year. Improvements in the structural analysis process are dramatically reducing the cycle time for structural sizing, to the point where application of detailed structural analysis is becoming practical early in the configuration definition cycle. This paper discusses several technologies that enable this acceleration of the structural sizing process. They include rapid generation of finite element models (FEMs), parametric modeling, rapid calculation of aerodynamic loads, faster structural sizing for strength and for dynamics, rapid estimation of vehicle mass and its distribution on the FEM, rapid local sizing of panels, and rapid sizing of the thermal protection system (TPS).

Introduction

Configurations of aerospace vehicles have historically been developed in a sequential process in which the fidelity of analyses increases as the level of definition of the configuration is increased. At the earliest stages of a program, the gross vehicle characteristics (payload weight, fuel volume, wing area, target mass fractions, etc.) necessary to meet the mission requirements are selected without a real configuration definition. Once the range of the gross parameters is defined, a configuration designer begins outlining candidate configurations within that range. At this stage of development, a configuration definition consists mainly of a three-view sketch of the vehicle, the outer mold line (OML) definition, and a layout of major systems.

Since a wide variety of possible configurations can be defined that satisfy the gross vehicle characteristics, a set of trade studies or an optimization is performed to further refine the design. At this stage, the vehicle definition is driven primarily by aerodynamic considerations (aerodynamic performance and stability & control). The aerodynamic analysis used to evaluate configurations is typically a linear aerodynamic code, but in some cases might be higher-order computational fluid dynamics (CFD). Many of the systems requirements (i.e. total fuel volume, engine thrust, actuator requirements, etc.) can be estimated based on the aerodynamic calculations. Typically at this stage of vehicle definition, the structural aspects of a configuration are estimated using highly simplified models, such as areal or volumetric weights, or perhaps parametric weight equations. Using processes such as these, a reasonably good assessment and refinement of the vehicle is usually performed, and a successful vehicle configuration is the outcome.

Once the candidate configurations have been narrowed down to a “best” configuration, a more detailed assessment of the vehicle is performed. This involves a higher level of fidelity analysis in all disciplines. In the structures area, structural FEMs are constructed, loads are calculated, and the structure is sized based on the calculated loads. Depending on the configuration and the mission, other analyses might also be required such as Thermal Protection System (TPS) sizing, aeroelastic loads, modal frequencies, aeroelastic and aeroservoelastic stability, and aerothermoelastic interactions. There are many outputs of this structural analysis. The most obvious is an estimate of the structural weight of the vehicle. This weight estimate is typically more accurate than the simplified weight estimates used earlier in configuration definition, and can be used to refine the vehicle performance and viability assessment.

A much less obvious output of the structural analysis and sizing process is the identification of structural show stoppers. In the development of conventional configurations for which a large body of experience is available (e.g. body and wing subsonic aircraft), it is rare for real show stoppers to appear that make a configuration infeasible. This is due to the fact that configuration designers have been working with these configurations for many years, and have the benefit of having seen many successful (and some unsuccessful) configurations. For the most part, the pitfalls are known. However, when unconventional configurations are being designed (and certainly all reusable launch vehicles must be considered unconventional at this time), there is a much smaller heuristic experience base upon which to draw, and it is very possible that an unforeseen structural issue will prove to make the configuration impossible. Since this process has historically taken six months to a year, many man-years of effort could easily be wasted on configurations that have show stopping structural issues.

It is clear that structural analysis and sizing earlier in the configuration definition cycle would be valuable, both by increasing the fidelity of the early performance estimates and by identifying show-stopping issues before a large amount of resources have been committed. In the past, the reason structural analysis and sizing have not been included early in the design cycle is the lengthy structural analysis and sizing cycle time (several components of which are described below). An analysis cycle of six months to a year simply cannot be included in configuration trades that may turn around several times a month. Fortunately, improvements in structural analysis processes and approaches are dramatically reducing the cycle time for structural sizing to the point where it is almost possible to insert detailed structural sizing into the early configuration definition cycle.

This paper will discuss several enabling technologies for accelerating the structural sizing process to the point that it is useful in early studies. The key items for making this happen can be classified according to whether they enhance the sizing process itself or speed up the preparation of inputs to the sizing process:

Vehicle Sizing Process

- Global Sizing
- Global/Local Interface
- Local Sizing

Rapid Input Generation for Sizing

- Parametric Modeling
- Rapid FEM Generation
- Rapid Loads and Dynamics Analysis
- Rapid FEM Mass Estimation and Distribution

Each of these technologies will be discussed, and the current state of the art will be assessed. The ongoing development of an integrated rapid structural analysis and sizing framework will also be discussed, as well as several applications of the sizing process to realistic configurations.

Vehicle Sizing Process

Although the major factors contributing to the cycle time for structural sizing are related to the setting up of vehicle models and other analysis inputs, it would be helpful to first consider the sizing process itself. The process is shown graphically in Figure 1, and clearly is very multidisciplinary and involves many steps. This review will provide an understanding of the requirements which the vehicle FEM and the other analysis inputs must satisfy. There are also features of the sizing cycle where improvements can reduce cycle time, and these are worth pointing out.

There are, as mentioned previously, various instances of structural analysis during the development of a vehicle. However, this discussion is concerned primarily with the analysis that is performed when a FEM of the vehicle is ready. The focus of this paper is on the technologies that enable this particular form of analysis to be applied earlier in the configuration development cycle, so it is important to clarify what it involves.

Global Sizing

The core of the sizing process is the optimization of the vehicle FEM at a global level, usually in MSC/NASTRAN. Here, the structure is typically sized to minimize weight while satisfying constraints which can include allowable stress and strain in materials, limits on internal running loads, vibration mode frequencies, flutter speed, and so on. When the global optimization converges, a series of analyses follow to check things that are not captured in the global FEM.

Since the series of analyses that follow the optimization of the global FEM are each capable of changing the properties, loads, weight, and geometry (in the case of TPS offset) of the vehicle model, the global optimization needs to be repeated. The entire sizing cycle, from global to local and back, has to be repeated until convergence is achieved.

The iterative nature of the sizing process, and the use of several analysis codes to complete each iteration, indicate that streamlining the transfer of data from one code to the next will make the process run faster. In converting the results of one program to input for another, the less manual intervention necessary the better.

Global/Local Interface

The primary data from the global optimization that are used in the local sizing analyses are internal loads in the sized structure. The loads are associated with the local structure being sized in each analysis, and are therefore extracted, averaged, or otherwise processed from global FEM results. The processed loads are accompanied by other information about the vehicle structure, such as thickness limits or joint concepts, that complete the input for the local analyses.

When the global optimization converges, the model needs to be updated to obtain the final loads. Since the structural sizing may significantly affect the weight and balance of the vehicle, the first step is to update the distribution of fuel and payload to ensure that rules about total weight and center of gravity (CG) limits are satisfied. Once this step is complete, the appropriate analyses are performed, using the sized vehicle FEM, to update the external and internal loads. Depending on the vehicle, these can include static analyses, static aeroelastic analyses, thermal analyses and others. These loads are used for various analyses outside the global FEM.

On completion of the local sizing, the information to be passed back to the global FEM includes updated properties for finite elements, updated nonstructural mass distributions, and updated geometry (when TPS sizing is performed).

Clearly, there is a lot of data transfer between the global FEM and various local analysis codes. Much of the translation of FEM results into input for these codes depends on FEM characteristics. For example, a code that checks panel stability needs the average loads from the finite elements that make up that panel, a code that estimates joint weight needs the running load across the joint, and a code that sizes TPS at a given point needs to know the location of the point relative to the leading edge of the wing and the material, structural concept, and structural sizing results at that point. Ideally, the transformations to be applied to FEM results for each code would be set up automatically when the FEM is created.

Local Sizing

The global FEM does not capture the weights of joints, fasteners, and other local reinforcements for features like hatches and doors, which are collectively known as non-optimum weights. Using the updated internal loads from the previous analysis, these features are analyzed and weights are computed. The tool used at Boeing for this process is called XFEMWTS. The output from this step consists of nonstructural mass increments to be applied to the FEM to account for the non-optimum weights.

The global FEM also is not capable of analyzing individual panels in skins and in substructure webs for stability, and other detailed checks that depend on the structural concept of the panel, such as stringer crippling or shearing in the core of a sandwich panel. For these checks, Boeing codes like ADVISOR or commercial codes like HYPERSIZER are used. These inputs to these programs are loads from the FEM that have been averaged in some way to correspond to individual panels (which may consist of dozens of elements in the FEM), and a description of the design space in which to operate. The design space consists of parameters that define the structural concept of the panel, like stringer spacing and skin thickness, and the input specifies the ranges of values of these parameters that are to be searched for the lightest design. Different structural concepts can also be compared in this process. The output from these programs is the lightest panel that can satisfy all the checks performed (buckling, crippling, stress, etc.), and the process provides updated properties for the corresponding elements in the FEM.

If rules are available to define what can and cannot be manufactured, the structure can be checked for them at either the global or local level. For manufacturing factors that affect the details of the structure, local analyses are necessary. For vehicle level guidelines, such as limits on running loads in the vicinity of manufacturing splices, constraints are implemented in the vehicle FEM and addressed during global optimization.

For hypersonic vehicles and launch vehicles that employ TPS, the sizing of the TPS should be integrated with the structural sizing. The structural OML is offset from the aerodynamic OML by the thickness of the TPS, and this difference can be significant for structural loads in certain situations, for example when a wing is thin compared to the TPS. At this step in the sizing cycle, the TPS is sized and its weight is changed, and the structural OML is updated as well. In other words, the local of the structure in the vehicle FEM is changed.

Rapid Input Generation for Sizing

It is in the task of setting up the FEM and other sizing process inputs that the most time can be shaved off the sizing cycle. This task is the most labor intensive part of the entire structural analysis cycle, but that is not the only reason. If the preparation for the sizing process is carried out well, the process will execute faster. In the description of the sizing process it was mentioned that the execution of the sizing cycle could be quickened by automating data transfer between analysis codes in the cycle, and that the translation of these data needed information that could be provided when the FEM is generated. These facts indicate that technologies that reduce the set up time for the sizing process, and ensure that the right inputs are available, have great promise for reducing the cycle time for structural sizing to the point where it is practical to apply it early in the development of a vehicle configuration.

Parametric Modeling

If the vehicle sizing process described above is to be applied earlier in the development of a configuration, there will be a need for adapting to changes in the configuration. Even in the traditional sequence of events, the configuration often undergoes revisions during and after the stage where an FEM is being used for analysis. Setting up an FEM has traditionally taken so long that it is not possible for structural analysts to keep up with the latest configuration changes. One approach to address this problem is the use of parametric modeling.

The basic idea of parametric modeling is that by describing a configuration in terms of basic parameters, and by making an FEM dependent on these parameters, the FEM can then be adapted to a different configuration by changing the values of the parameters accordingly. This is easier said than done, because the interdependencies between parameters can get quite complicated. Parametric modeling has been implemented to varying degrees in different places.

Examples of parameters that describe configurations include global quantities like wing span, body diameter, and weight, as well as structural layout descriptors like rib spacing, the number of spars, and bulkhead locations. To define a configuration in more detail, parameters like the structural concepts employed in different parts of the vehicle, the materials used, the locations of nonstructural masses like actuators and landing gear, and the locations of control surface hinges may be specified. Some of these parameters may be defined independently of others, or as functions of one or more parameters. Depending on the vehicle and the level of fidelity intended for the FEM, the number of parameters and the complexity of the relationships between them can be small or large.

Generally speaking, there seems to be more capability for parametric modeling in the world of computer aided design (CAD) than in the realm of finite element preprocessors. There is a parametric modeling facility in UNIGRAPHICS that allows parameters and relationships between them to be defined by algebraic expressions, which are used to maintain the relationships when individual parameters are changed. This facility is not only capable of generating new CAD models from a set of parameters, but of updating an existing model when a parameter is changed as well.

Among graphical finite element preprocessors, IDEAS has a parametric capability that permits models to be updated when parameters are changed, while PATRAN bases its parametric features on regenerating the model whenever one or more parameters need to be changed. This capability of PATRAN is based on its so-called session files, which store all the commands that were executed to create a model in the form of function calls in PATRAN Command Language, or PCL. When a session file is replayed in PATRAN, the same commands are executed again in the same sequence. If nothing is changed, the same model is created again, but by changing the arguments passed to the PCL functions, the model they create can be altered. When the parametric feature of PATRAN is invoked, during the creation of the model in the usual interactive mode, the session files that are written have variables instead of values for quantities that have been identified as parameters for later use. These session files can be replayed after supplying values for the variable parameters to create variants of the model.

Even before the implementation of this parametric feature in PATRAN, session files were being used to achieve parametric modeling capability. With some familiarity with PCL and session files, this is not a difficult task. This was demonstrated by implementing parametric modeling using session files for an FEM of a Blended Wing Body (BWB) test model known as the Low Speed Vehicle (LSV), shown in Figure 2. One pleasant surprise in this case was that it actually took less time to set up the FEM by focusing on session files that it did by the normal, interactive way. This was because, when the same command needs to be repeated several times, it's quicker to copy the PCL calls and modify the arguments in a text editor than it is to point and click the mouse through all the menus each time to generate the same session file. The real savings in time come when variations of the model needed to be generated. The amount of time saved depend on the type of change being made. A change in loft shape, for instance, would have required that the model be effectively re-built from scratch in the traditional approach, compared to which replaying the session files with the new loft was very little work. At the other extreme, a simple change of materials would be very little work with either approach, so parametric modeling would save little time. When the total effort is considered, including set up time and numerous variations of the model, parametric modeling offered significant time savings. The relative efforts required for conventional and parametric modeling for the LSV configuration are shown in Figure 3.

The drawback of parametric modeling is the possibility of excessive complexity. With a detailed model, when there are many parameters, and they are interrelated, defining the relationships and properly maintaining them requires organization and a robust, user friendly tool. With the session file approach in PATRAN, it is necessary to be aware of the consequences of changing a parameter, not just in the first command that uses it, but far downstream in the sequence of commands being executed. In a complex model with hundreds of operations required to create it, this task can be daunting. As tools for parametric modeling develop further, the analyst will be able to worry less about organizational details and bookkeeping, and models will be easier to make parametric.

Rapid FEM Generation

Whether or not a model is parametric, a major contributor to the lengthy cycle time of conventional structural sizing using FEMs is the preparation of the FEM. Speeding up the process of building the FEM goes a long way towards reducing overall cycle time.

An FEM is typically based on geometry data that describe the OML shape, and a definition of the layout of structural members within it. Initial estimates of structural sizing and of inertia properties complete the model. Configuration designers are commonly the engineers in charge of the OML geometry, though it is common for them to receive input from aerodynamics engineers at early stages of configuration definition. The layout of structure within the OML of the vehicle is determined by the configuration designers also. Their definition of the configuration is usually in the form of a drawing in a CAD package such as CATIA or UNIGRAPHICS. The initial structural sizing and mass properties of the configuration are provided by weights engineers or the configuration designers themselves, but are usually stored outside the CAD model.

Although CATIA and UNIGRAPHICS have some meshing capability, the most common practice is to build the FEM in using graphical preprocessing software like PATRAN and IDEAS. These programs permit the FEMs to be generated for a variety of analysis codes such as NASTRAN and ABAQUS. Although there are various tools available to transport the geometry data from CAD software to the FEM preprocessor, and a variety of intermediate neutral formats in which the data can be exported from one program to be imported into another, in practice the importation of CAD geometry into FEM preprocessors is often problematic. At a minimum, good communication between the CAD engineers and the FEM builders is required.

To generate an FEM rapidly, it is desirable not only to avoid a lengthy translation of CAD geometry for an FEM preprocessor, but to also to reduce the time spent preprocessing the FEM. Different approaches to this end are possible. The common feature that the approaches discussed here share is that they take advantage of their application to a particular class of structures, namely aerospace vehicles, to simplify the data required to define the structure. Broadly speaking, these vehicles can be described by the OML geometry combined with a substructure layout. Typically, much of the substructure is made up of planar members like spars and frames, and therefore the layout of the substructure can be defined in a two dimensional (2D) planform. The 2D layout description is simple to define and can be combined with the OML definition to create an FEM, using a tool developed for this purpose.

The above approach has been implemented on both sides of the CAD to FEM divide. One tool that operates within UNIGRAPHICS has been developed at Boeing, and it uses a 2D layout definition to break up the CAD geometry into pieces corresponding to the substructure elements. The subdivided geometry can be translated into PATRAN where it is ready for meshing without a need for time consuming refinement. This tool is called MANIAC. Another tool being developed at Boeing works independently of the CAD package, and internally combines the 2D layout definition with OML geometry to produce a three dimensional (3D) FEM. This tool, called RAPIDFEM, will operate on geometry from various sources, and is currently being used with an aerodynamic geometry definition from a CFD model. The 2D layout definition is provided to RAPIDFEM in a simple text file, and the FEM it generates is output in MSC/NASTRAN format. The modular nature of this tool makes it a simple task to accommodate the input of different geometry formats, and to generate FEMs for various analysis codes. A typical application of RAPIDFEM to the generation of a global finite element model of a wing (including winglet and control surfaces) is shown in Figure 4.

A benefit of using a 2D layout definition to generate a 3D FEM is the possibility of integration with CAD models, such as those generated with the parametric modeling facility in UNIGRAPHICS. The 3D CAD models in UNIGRAPHICS contain substructure members that are displayed from data stored internally in 2D, and when the CAD models are varied parametrically, the internal 2D layouts are changed. These layouts can be exported for use with tools like RAPIDFEM. The corresponding 3D OML data needed for RAPIDFEM can also be obtained from the 3D CAD model.

A difficulty in using a 2D layout to define a configuration is in handling attachments and interface structures between major components of the vehicle. Structure that connects a wing to a body is often unique to each configuration, and although it can be an important driver for sizing portions of the wing and the body, it is often difficult to create during the process of projecting the 2D layout through the 3D OML. The same is true for thrust structures that support launch vehicle engines, which are often comprised of trusses. The way such structures are handled is to generate the rest of the vehicle model using the automated process, and to later add these structures to it. The addition of these unique structures to the model can still be automated, and has been done using PATRAN session files or even FORTRAN codes, but it remains a separate step following the rapid FEM generation process. Figure 5 shows an example of a full-vehicle finite element model, where the wing is generated by RAPIDFEM, and the body and interface structure generated using traditional finite element modeling tools.

With a tool like RAPIDFEM, the generation of the FEM from the input data is so fast (literally a matter of a few minutes), that the ability to update an existing FEM for a change in a configuration parameter is not necessary. As long as the OML geometry and the 2D layout can be updated parametrically, the new FEM is immediately available.

Rapid FEM generation makes it possible to start the vehicle sizing cycle sooner. The optimization model for MSC/NASTRAN is provided by the FEM generation tool in much less time that it traditionally takes to set it up. To continue with the sizing cycle, inputs are needed for the various other analyses that comprise the complete global-local loop. Much of the information that needs to be provided to these analytical tools comes from the FEM. By integrating the rapid FEM generation tool with these other programs, the inputs are set up at the same time that the vehicle FEM is generated. The areas where integration of FEM generation with generation of input for other pieces of the structural sizing process is shown graphically in Figure 6. This approach reduces the set up time for running the vehicle sizing process even more.

Rapid Loads and Dynamics Analysis

Of course, the finite element model and the accompanying sizing process is of little value if accurate sizing conditions are not available in a comparable amount of time. The most important of these are the critical load conditions. It is fairly simple to rapidly estimate flight loads based on low-fidelity aerodynamic theories such as linear lifting surface or panel codes, or semi-empirical codes such as S/HABP. Unfortunately, the resulting critical load distributions are often inaccurate because the flight regimes are often extreme (high anble of attack, large control surface deflections, transonic mach regime, etc…). Since loads are such an integral piece of the sizing process, it is important that they be as accurate as possible, and relying on low-fidelity aerodynamic codes is not desireable.

In the past (and to some extent, currently), there has been an enormous cost and schedule barrier to using higher fidelity aerodynamics. Experimental aerodynamics is obviously very slow and costly due to the need to construct wind tunnel models, obtain access to a suitable facility, and reduce the mountains of data generated. Computational Fluid Dynamics (CFD) has also been prohibitive due to the large man-hour requirements to construct the analytical models (grids), and the large computer-hour requirements to generate the solutions. This problem is magnified by the need to compute in excess of 1000 aerodynamic solutions to support a robust critical loads survey.

Fortunately, there are several rapidly maturing technologies that will dramatically lower the barriers to rapid high-fidelity loads analysis in the next few years. These can be broadly grouped into (1) computing advances, (2) modeling/gridding advances, and (3) overall process advances.

Advances in the price/performance ratios of available computing platforms have been phenomenal, and the trend shows no sign of reversing. Of particular interest is the use of low cost “commodity” computers based on the personal computer architecture (Intel/AMD) that is beginning to offer supercomputer performance for an order of magnitude lower cost than “traditional” high performance computing. This is especially exciting in the context of parallel computing using PC clusters, which is proving to be a very effective approach.

In the aerodynamic modeling technology arena, there are two facets that are of interest to the loads process. The first is to define the requirements for a CFD grid for loads analysis, and the second is to generate that grid. A careful examination of the quantities of importance to the loads analyst (and the sensitivities of these parameters to grid parameters) gives some important insights. First, it cannot be overemphasized that the goals of CFD analysis for loads calculation are quite different than those of CFD analysis for aerodynamic performance calculation. In loads analysis, the primary quantities of interest are lifting surface and body bending moments, shears, and torques, along with control surface hinge moments. It is often possible to capture these quantities very accurately with a CFD grid much coarser than that required for accurately predicting “typcial” aerodynamic performance indicators, such as drag and maximum lift coefficient. An example of this is shown in Figure 7, where a “fine” grid suitable for aerodynamic performance analysis was coarsened by a factor of 2 to give a “medium” grid, which was again coarsened to give a “coarse” grid. The medium grid has one eighth as many grid points as the fine grid, and the medium grid has $1/64^{th}$ as many grid points. The body bending moment distributions computed using the coarse and medium grids indicate almost no difference, indicating that the coarse grid is probably adequate for body bending loads calculation. While the coarse grid is not adequate for calculating all load parameters (particularly control surface hinge moments), the medium grid typically gives good loads results with almost an order of magnitude fewer grid points than required for performance calculations.

Within the grid generation topic, there are again two problems to considered. The first, of course, is the generation of a robust grid around a baseline configuration in a reasonable amount of time. Using current structured-grid technology, this process can take over a month for a complex configuration. However, advances in unstructured-grid technology for viscous flow solutions will probably provide huge benefits here, and we can expect to be getting viscous CFD grids of entire configurations in a matter of days or hours instead of weeks. The second grid-generation aspect that is required for loads analysis is grid perturbation. It is often the case in loads analysis that the baseline grid must be modified slightly to account for control surface deflections or aeroelastic deformations. While the modifications are small, they must be done many times (on the order of thousands), and must therefore be entirely automated. When the grid generation technology is sufficiently mature, it may be feasible to simply regenerate the entire grid for each perturbation, but for the time being, grid perturbation approaches appear to be more viable. There are several grid perturbation approaches available [hartwich, farhat, etc…], mostly targeted at aeroelasticity.

The third area of discussion is the overall loads analysis process. Current loads analyses are usually based on the concept of an aerodynamic “database” made up of wind tunnel or CFD aerodynamic data. To compute the loads at a given flight condition, the database is interrogated for the various pressure distributions, increments, and corrections that apply, and these pieces are combined in the appropriate combinations to give an estimate of the trimmed, aeroelastic loads for the flight condition in question. This approach is beginning to change as a result of the technologies described above. It is currently feasible to directly compute aeroelastic, trimmed flight loads as a part of the high-fidelity aerodynamic solution. This process has been applied to generate trimmed flight conditions for a re-entry vehicle, in which the flaperon and ruddervator deflections were dynamically updated as part of the CFD solution to directly generate the pressure distribution for a trimmed flight condition at convergence. If the technologies discussed above continue to advance as expected, we may find that direct CFD-based trimmed loads analysis can be used to rapidly and accurately estimate critical flight loads, especially for trajectory-based vehicles.

Rapid FEM Mass Estimation and Distribution

For load conditions involving any acceleration of the vehicle, correct inertia properties are important. When FEMs are created, there is usually available some sort of estimate from configuration developers of the mass properties of the vehicle. If this weights statement is fairly detailed it can be a significant effort to put nonstructural mass density and concentrated nonstructural masses into the FEM to match the estimated weight. Accomplishing this task manually involves a lot of calculations using locations of FEM nodes, CG locations of nonstructural masses, areas of FEM elements over which nonstructural mass is to be smeared, and so on. There are many opportunities for cycle time reduction by automating these tasks.

The estimation of the inertia properties of and FEM is possible with various tools, ranging from the analysis code itself (for example MSC/NASTRAN), to the finite element preprocessor (such as PATRAN), and even independent codes (in-house tools have been implemented at Boeing). A stand alone program that can generate a weights breakdown using an FEM as input is a surprisingly useful tool. In addition to verifying that added masses had the intended effect on vehicle inertia properties, such a tool assists in debugging an FEM by indicating missing weight, and is useful for tracking the results of vehicle sizing by revealing the parts of the structure that were resized by the optimization.

Fewer options are currently available to distribute nonstructural mass on an FEM. There are in-house programs that process an existing FEM to determine the inertia of subsections of the FEM, and then add mass to make them match target values. Such codes take some time to use, since the FEM needs to be broken into groups defined by the analyst. A different approach is used in the RAPIDFEM process mentioned previously, in which the individual mass items from the weights statement are input to the program, and it places them appropriately in the FEM.

A key point in the RAPIDFEM approach to distributing nonstructural mass in an FEM is the use of the 2D layout of substructure. This avoids a common pitfall of concentrated mass elements – if they are placed on structure that is inadequately supported, the FEM computes spurious local vibration modes, excessive deformations under acceleration, and so on. The 2D layout only includes major structural members, all of which are capable of adequately supporting the masses of the various items contained in the vehicle. By indicating the parts of the 3D FEM corresponding to these pieces of sturdy substructure, the 2D layout guides the application of mass to proper locations in the FEM.

Using the above approach, each mass item in the input, such as an engine, a control surface actuator, or an avionics box, may be described by several FEM mass elements, but the input is just the mass of the item and its CG location. Using straightforward logic to match the total mass and CG of the FEM mass elements to the specified values completes the task. Much time is saved by the fact that the input to the process closely resembles the weights statement provided by the configuration developers. An added advantage is that the masses representing individual items are traceable, so that items are easily removed from, or added to, the vehicle FEM.

Conclusions

Reducing structural sizing cycle time permits FEM based structural sizing to be applied early in configuration development, to the benefit of the vehicle development effort.

Rapid generation of FEMs and other sizing process inputs are key technologies to reduce the set up time as well as execution time for the structural sizing cycle.

The use of a 2D layout representation of major structural components as the reference point for the structure of a vehicle facilitates rapid FEM generation and modification, and can make it possible for structural analysis cycles to be completed in the timeframe of a configuration update.

References

Hartwich
Farhat
ICAT
SHABP
PANAIR

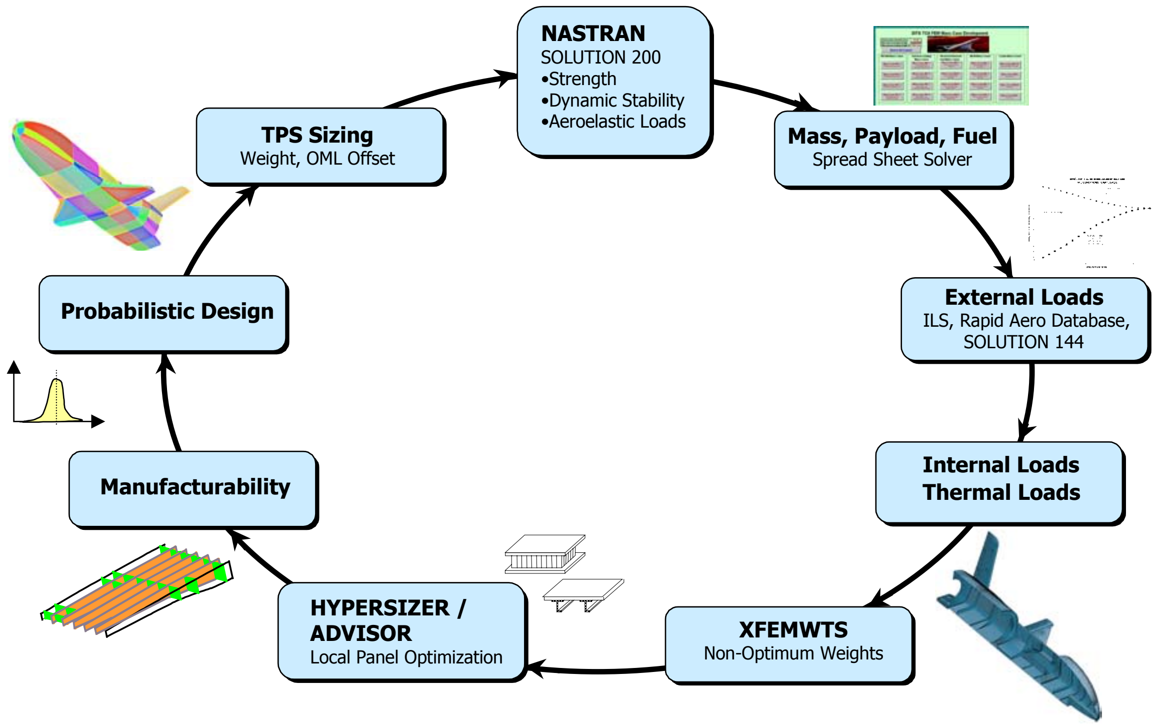

Figure 1: Vehicle Sizing Process

Figure 2: FEM for Parametric Modeling Illustration

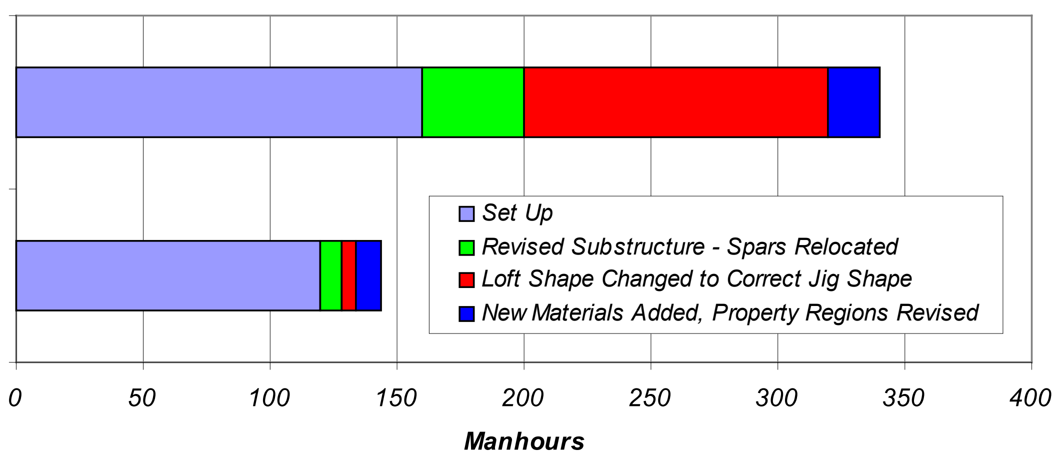

Figure 3: Time Saved with Parametric Modeling

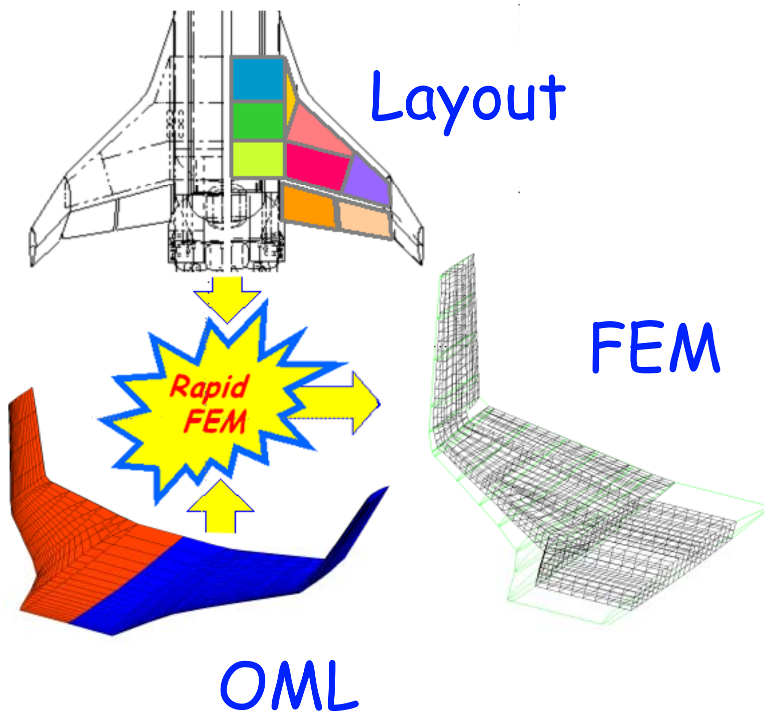

Figure 4: Rapid FEM Process

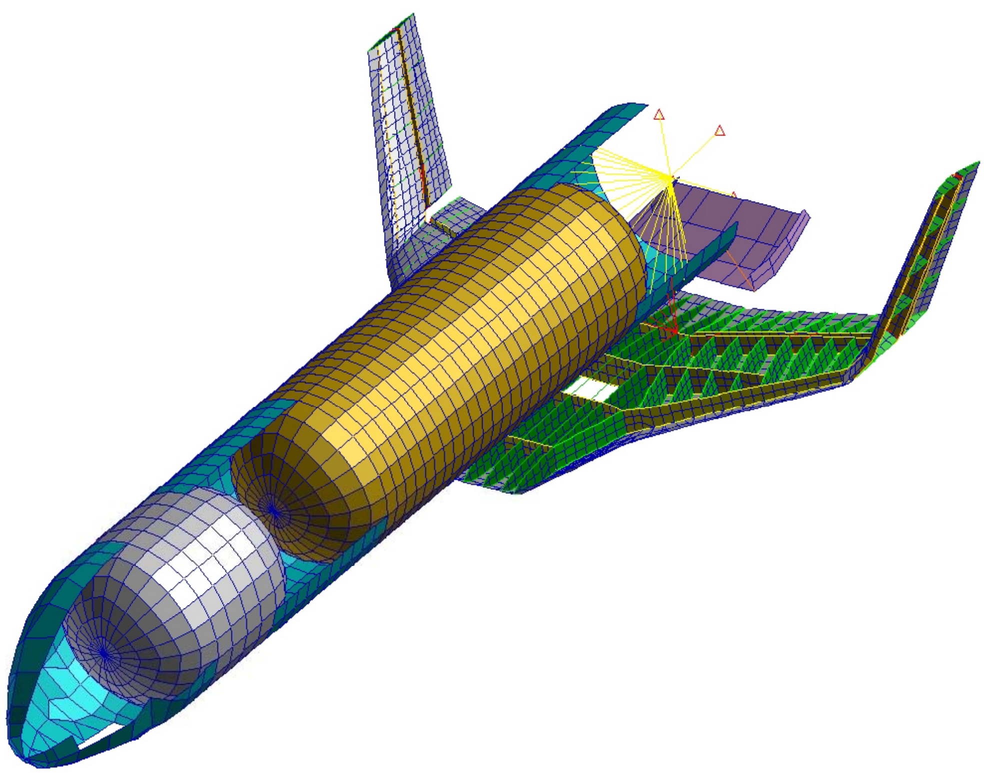

Figure 5: A Vehicle FEM, with the Wing from Rapid FEM

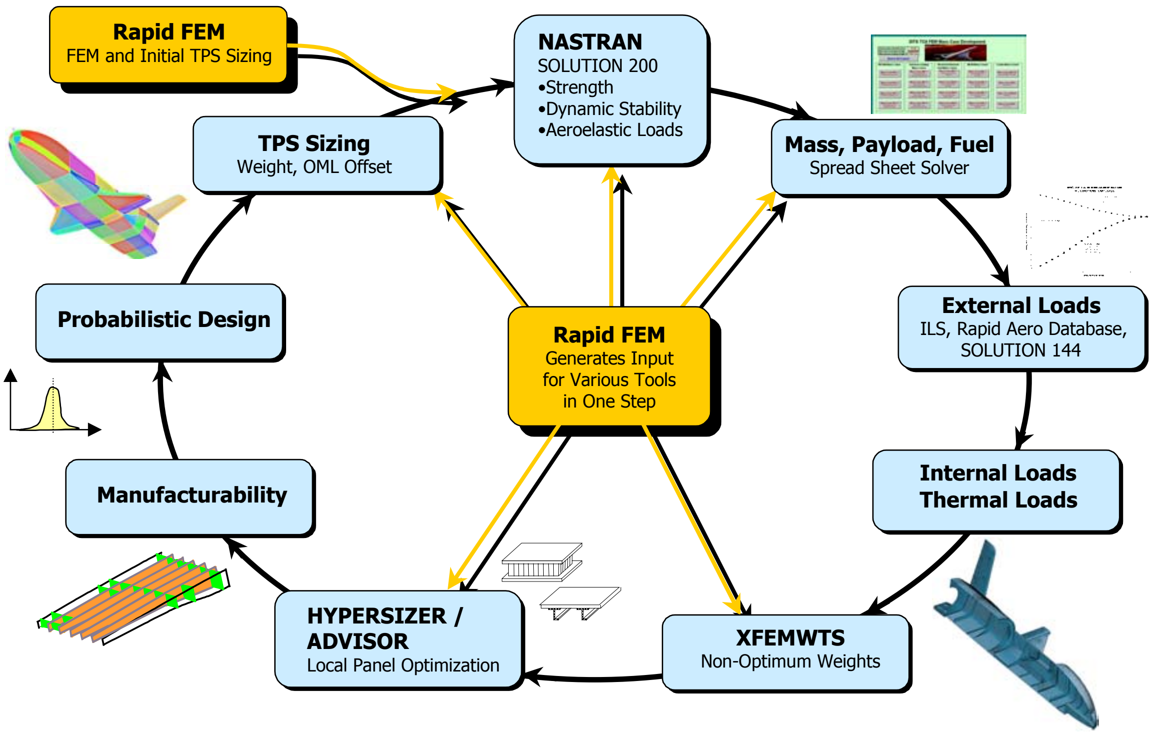

Figure 6: Rapid FEM Inputs to Vehicle Sizing Process

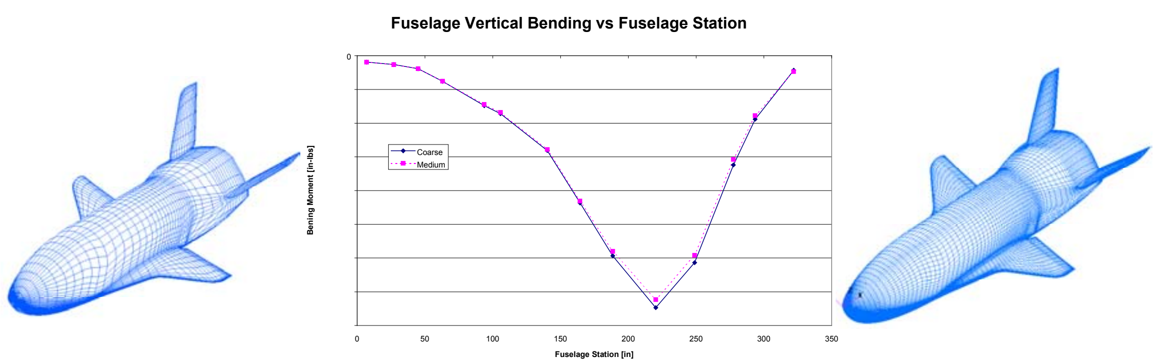

Figure 7: Control Surface Deflection and CFD-Based Trim Process