THE F-22 STRUCTURAL/AEROELASTIC DESIGN PROCESS WITH MDO EXAMPLES

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Abstract

Documented experiences of Multidisciplinary Optimization (MDO) applications during the engineering, manufacturing, and design phases of fighter aircraft programs are not numerous. Documentation is even rarer for aircraft that have flown. This paper describes in general terms the overall design experience of the F-22 fighter, and rapidly focuses on the aeroelastic/structural considerations where MDO like processes were employed. Central to the design process is the Air Vehicle Finite Element Model (A/V FEM). The A/V FEM is the common element to link design requirements and processes for loads, flutter, stress, dynamics, and control law design. Multidisciplinary aspects of the interdependent processes includes stiffness tailoring for meeting flutter requirements, control law tailoring for redistribution of external loads, flex to rigid tailoring for satisfying handling qualities, stress sizing and aeroservoelastic filter design within the general subject of aeroelastic optimization. The investment of using a controlled A/V FEM for loads, stress, flutter, dynamics, control law integration, weight estimation, etc., was to a significant measure responsible for the excellent stiffness and loads tailoring which resulted in a minimum weight design while satisfying the airplane performance requirements & allowing for the structural design parameters to be successfully iterated. The large A/V FEM was manageable in terms of configuration control, integration with specific discipline analysis processes, overall tracking/storing, and processing terabytes of data. The recovered cost of using a large model was returned many times over by savings in man-hours than if structure decomposition/back transformation methods had been employed. A very detailed loads grid, fuel tank fuel-vapor boundaries matched to maneuver attitude and g loading, and detailed internal and external pressure loading were other challenges successfully achieved to satisfy the Integrated Product Teams (IPT) requirements. The procedure for modifying panel flexible pressure loads to reflect non-linear wind tunnel rigid pressure distributions, especially due to control surface deflections, provided a high degree of fidelity to the flex to rigid and flex loads calculations. Finally, the computer access for the users drove all the necessary MDO like processes. The computational power and ease of use provided a capability to successfully manage the terabytes of data across wide area networks and many types of computing platforms. Additionally, the storage of results in relational databases provided fast and direct answers to questions with real time qualifications.

Introduction

The road to a production F-22 fighter started with concept studies during the mid-1980's and a prototype fly off under the banner of Advanced Tactical Fighter (ATF) which was concluded in December of 1990. Participants which included competing teams and multi-company collaborators had a number of role changes as the project came from behind the tightly closed doors during the concept days and into a more visible prototype days. The project is in the Engineering, Manufacturing and Development (EMD) phase. Full envelope expansion is planned to start in May 98 for ship 4001 at Edwards Airforce Base after a successful series of first flights conducted in Marietta during the third quarter of 1997.

The deciding milestone for the project came on the award of the EMD contract to Lockheed in first quarter 1991 after the conclusion of the prototype flight test program. The Lockheed prototype design demonstrated adequate performance, LO, and maneuvering characteristics. With the external geometry basically fixed, the focus of the design shifted to internal arrangement and design developments to satisfy maintainability, supportability, etc. requirements with weight as the principal metric for satisfying performance requirements.

Late in 1991, a number of trade studies were integrated into the design to help manage the challenging weight constraints. These studies foreshortened the fuselage by two feet and set the main landing gear configuration in the wing. There were also minor changes to the planform of all lifting surfaces and control surfaces based on refined wind tunnel force models.

There are many interrelated requirements and constraints, which enters into the design process and consequently the evolution of the design. This paper will focus on the design to data development, which was required to evolve the structure concepts and design.

Six areas were available to define the basis for the structural design:

- Basic geometry; materials initial structural definition.
- External loads driven by Airplane Simulator Responses due to Maneuvers defined in the Loads' Criteria and Weight.
- Flexible to Rigid Ratios.
- Stiffness/Mass distribution for Flutter Margin Requirements
- Vibroacoustics environmental definitions and high cycle fatigue design
- Flight Control Laws and Aeroservoelastic Stability Requirements.

The integration of various disciplines represented by the foreshortened list of six is largely governed by the constraints imposed by many competing requirements. Ideally, full derivatives would be derived for aircraft performance, LO signature, weight, equipment placement, maintainability, affordability, external loads, stiffness requirements, etc. with respect to each of a very large number of design variables.

Structures decided during the EMD proposal phase that an approach would be pursued which would return to the Project the greatest value for the resources expended. The core issue for this approach was the utilization of a single vehicle FEM for all derived design to data used to design the Structure:

- Vehicle loads (external, internal, internal pressures, etc.),
- Flutter and dynamics assessments,
- Flexible to rigid ratios,
- Extraction of material design allowables,
- Aeroservoelastic analyses.

A balance in the vehicle FEM detail between accuracy and affordability was driven by the following requirements:

- The vehicle FEM had to have sufficient detail for internal loads definition
- Model size could not overwhelm:
    - Databases for tracking and managing the many FEM configurations (symmetric, anti-symmetric, left, right, and control surface deflections)
    - Data management and computer usage requirements for using the vehicle FEM without alternation by Flutter and Loads

Time lags in data availability appear due to the various processes schedule requirements and the sequential nature of the inter-related processes. In addition, some design decisions must be done early into the design process before a good definition of the structure is known, such as locating the flight controls sensors.

The summary of the process flow for structure design to data is found in Figure 1. The data flow shows that loads and flutter analyses are performed using a FEM (-1) which is one design (model) behind the FEM (0). More importantly, there are lags up to 3 design cycles for new flexible to rigid ratios and loads tailoring data to be incorporated into an updated flight simulator. Changes like loads tailoring had to first go through control law development cycle. Stress allowables, which define fatigue life requirements, may lag the process by 2 or more cycles. As bad as this may appear, as measured by external loads, stiffness requirements, and control law developments, the process did converge. The major perturbation to the process was the changes coming from the Detail Design box. Here the variability in the sizing and model grid and element changes caused significant changes in internal loads for a near equivalent external load definition.

In addition, the process was further removed from the desired MDO approach because not all of the Integrated Product Team's (IPT) budget profiles matched the requirements of the Process Flow Chart for an orderly convergence. With minimum weight requirements dominating the structural design concepts, the IPTs dependence on fine grid structural sub-models grew. "Small" variations in load redistribution sometimes caused major shifts in margin calculations. This was a consequence of forcing mathematical zero margins in a fine grid FEM where large derivatives of internal load changes were possible for small changes in sizing or grid definition.

The efficient computing and data management systems employed in the F-22 design development may have produced a downside or two. The IPTs decided to ask for redistribution of external loads on fine grid FEM sub-models. This permitted the using of a model without going through the pain of understanding how the structure really works up through ultimate load. The computer showed how a particular FEM could be made to work without the proper controls on how well the FEM itself represented the structural concept. Good design concepts, which work on the hardware airplane, are the deciding factors for establishing an efficient structural system that are lightweight, robust, and cost effective while avoiding single criteria minimum weight solutions traps.

Statement of Problem

Documented experiences of MDO applications for fighter aircraft during the design development phases are not numerous. For aircraft that have flown, documentation is rare. The technical community knows the power of MDO and not having a cradle to grave example has been a continual source of frustration, as voiced by AIAA MDO technical committee members over period of years.

Scope and Methods of Approach

This paper describes in general terms the overall design experience of the F-22 fighter, and rapidly focuses on iterative aeroelastic/structural design processes (Figure 1) to highlight MDO like processes which were used. Central to the structural design process is the Air Vehicle Finite Element Model (A/V FEM). The A/V FEM is the common element for loads, flutter, stress, dynamics, and control law design to processes. Multidisciplinary aspects of the interdependent processes includes stiffness tailoring for Flutter requirements, control law tailoring for redistribution of external loads, flex to rigid tailoring for handling qualities, stress sizing, and aeroservoelastic filter designs within the general subject of aeroelastic optimization. Finally, there are lessons to be learnt from this exercise and in particular the special requirements of a fighter where volume is a premium and structural concepts may be inherently non-optimum shapes as opposed to transport aircraft where the volume permits fundamentally optimum shapes and concepts.

Team Interaction and Policies

To achieve a minimum weight design while meeting the performance goals required close coordination between the customer and contractor as well as among the contracting team members. As a result of this close coordination a tailored design criteria was established to keep the design constraints specific and relevant to the F-22. This entailed defining in close concert with the customer a structural criteria document that was specific to the F-22 usage and performance.

The team integration was achieved by instituting policies and guidelines that each of the tri-company team members would be required to follow. These included developing a common set of material properties, conducting analysis with common or equivalent software tools, and building an Air Vehicle Finite Element Model (A/V FEM). Additionally, significant effort was expended to ensure that the engineering design and analysis was closely integrated with ground and flight-testing. This was accomplished by developing detailed test plans in coordination with the customer that was specific to the F-22.

Air Vehicle Finite Element Model

The A/V FEM provides the foundation for the overall design process by providing a common basis for configuration control and analysis. The A/V FEM is the common interface for many disciplines as shown in Figure 2) to develop design to data. This single model is used to compute internal and external loads, flex-to-rigid ratios, flutter design requirements, and thermodynamic response. Figure 3 illustrates the size, complexity, and the number of configurations tracked for this single model. The individual super elements were built by the F-22 team member responsible for the structure and then assembled for analysis by the prime contractor Lockheed Martin Aeronautical Systems Company (LMASC). A very detailed set of guidelines was established and documented early in the program to ensure compatibility among the organizations developing the model. These included defining the numbering convention, definition of acceptable element types, and the use of defaults and parameters. Additionally, the document included definition of any requirements defined by the functional disciplines to support their independent analysis tasks. An example in this document was the requirement that the composite laminates be explicitly defined in the comment statements to facilitate aeroelastic sensitivity analysis at the composite ply level. The A/V FEM was manageable in term of configuration control, integration with analysis routines, overall tracking of the design, and storage/processing of terabytes of data. The cost of using a large model to generate aeroelastic design to data was insignificant compared to the savings in man-hours achieved by using one verified model whose configuration control and responsibility for accuracy was vested in one group.

External Loads

The air vehicle flight simulator drove computation of external loads for transient maneuvers defined in the loads criteria report. The rigid air loads were based on extensive wind tunnel pressure model test data. While the flexible incremental load distributions were derived using linear panel load methods, the panel loads were adjusted on component basis based on wind tunnel rigid integrated load values. The process permitted adjustments for non-linear effects especially near the control surface hinge line. Another unique feature of the load process was the computation of the fuel tank pressure distribution consistent with the fuel free surface orientation for the specific maneuver and fuel load distribution that was consistent with the load condition. Finally, hammer shock inlet pressure distributions were used based on computational fluid dynamics (CFD) analytical codes and test data.

A major milestone during the first year was the release of a full set of design loads based on CFD data. The loads latter agreed with the wind tunnel data to within 5 percent. The CFD released loads were for complete set of control surface deflections.

Load tailoring by Maneuver Load Control was established early in the EMD design phase. How much could the ailerons be used to dump the load inboard was a function of two design considerations. The first was the effectiveness of the ailerons and the second was the impact of the increased drag on performance. The points in the sky where the maneuver load control (MLC) could be most effectively utilized, however, was almost on top of the maximum performance point. There was aggressive tailoring of the control surface gain schedule to achieve weight benefits with MLC while holding the performance degradation to a minimum.

Load tailoring was achieved by minimizing adverse airplane responses during critical load's maneuvers. Close coordination with developers of flight control laws and quick turnaround for potential solutions on the flight simulation program were just two of the critical process that lead to successful closure. Load's engineers take six or more time hacks during each maneuver on the flight simulation. Critical loads are identified for reduction and the time hack and associated maneuvers are identified. Negotiations between Flight Controls and Handling Quality (HQ) engineers and Loads engineers establish proposed changes to the flight controls to tailor the loads. The cycle is complete when the changes appear in the flight simulation and a full load's analyses and a complete HQ studies show that the tailored loads have been achieved without introducing new issues for either HQ or Loads.

Loads and flex-to-rigid tailoring through ply lay-up optimization was attempted after the basic design was established. Studies were conducted for the wing and vertical fin surfaces. Derivatives for each of the ply directions did not show large gains without impacting other constraints. The ply directions for the wing proved to be near optimum for basic loads. The wing layout naturally encourages efficient ply direction allocation because of the planform geometry. The zero plies run parallel to the elastic axes for the outer wing. This is also true for the vertical fins. Buckling mechanism is another significant factor for each of these surfaces. During the prototype trade studies, predominant buckling mode improvements could be achieved if ply lay-ups had non-traditional orientations of (0,45,90). This is impractical from a materials testing point of view because of the costs associated with a greatly enlarge data base requirements. In each of these areas the weight penalty due to low derivative values required other options to be pursued.

Internal Loads and Margin of Safety

At Lockheed-Martin in Marietta, external loads for maneuvers and fatigue were processed through the vehicle FEM and the resulting internal loads were loaded into Oracle relational database. The designer and stress analyst had immediate access not only to the current loads released but also to past releases. The analyst then could compare what changed or work on different releases of the drawings.

With weight a significant factor in the design process, many parts had zero margins of safety when released. With changes in the internal loads, some of those zero margin areas could no longer support the new internal load distribution. In the course of the process that followed, the question was raised, "what is the flight envelope for the aircraft with negative margin?" A complex and data intensive methodology evolved where point analysis programs generated margin of safety values for some 3000 load cases and then through interpolation of flight conditions, contours of zero margin of safety were derived in the Mach and Altitude plane. Then Aircraft Operating Limits (AOL) were then determined for the aircraft within the structural capability and the derived limits based on what structural testing was completed up to that point. This margin of safety versus flight envelope methodology will be a significant aid as the airplane explores the testing envelope where critical load conditions exist.

Temperature Effects

Temperature distribution affects structural design in the selection of materials and in the introduction of thermal induced stresses. Material allowable for composites is a function of maximum temperature and amount of moisture saturation. Hot-wet properties for composites dominate the maximum temperatures allowed in the design. For aircraft structures constructed with dissimilar coefficient of expansion materials, such as mechanically joining of aluminum with composite components, thermal strains must be accounted for in the internal load definitions.

Flutter

Definition of the air vehicle flutter margin and the necessary design to data lagged the detail design by no more than a single design iteration and significant changes were brought back an iteration to implement in the aeroelastic model. Analysis metrics was established to facilitate tracking of the detail design. This included the definition of a procedure to compute, for each control axis, the total control loop stiffness, detailed weight estimates of control surface hinge-line inertia and center of gravity, and unit loads on the A/V FEM to track the structural flexibility.

The aeroelastic requirements were derived from sensitivity and optimization of the design parameters. The design variables consisted of three primary types: percent changes to physical properties such as cross-sectional area and skin thickness; composite laminate properties such as the addition of a single ply at a given orientation angle; laminate material axis sweeps where the material axis for an entire surface is rotated. Table 1.0 lists a breakdown of the variables on a per-surface basis. To facilitate defining requirements in terms of true sizing variables accurate and automated sensitivity analysis to aeroelastic parameters is required. The F-22 program utilized "in-house" specialized software for sensitivity analysis. Additionally, a powerful Convex computer was available with over a terabyte of disk and 10 terabytes of tape capacity.

Multiple complex analysis models and optimization was utilized to determine if a synergistic solution would provide a decrease in weight or increase in performance. For example, as part of the aeroelastic optimization process a strength heuristic constraint was implemented. The heuristic approach defined the amount of material that can be removed in an area when additional material is added while not violating strength requirements. For example, if the optimization calls for adding plies to a laminate at +/-45 degree's then either 0 or 90-degree plies can be removed, the heuristic algorithm constrains the amount to be removed. Additionally the process implements rules defined in the structural policy document such as keeping the percentage of plies at a given orientation angle within specified limits. F-22 structure effected by this type of sizing includes the vertical fin and rudder. Interestingly, material added above the strength size design for aeroelastic reasons at one design iteration turned out to be necessary in some areas for strength on the next design iteration.

Aeroservoelastic

Aeroservoelastic stability margins were defined by running a coupled analysis of the A/V FEM, the aeroelastic mass distribution, unsteady aerodynamics, and flight control laws. This multidisciplinary task was accomplished by Flutter organization by computing aircraft responses in the frequency domain and then coupling these responses with control law's supplied by Flight Controls. Both the control laws and the aircraft responses were computed for a set of mach/altitude/fuel loading /maneuver load conditions that spanned the flight envelope with a heavy concentration in critical regions. The process did iterate and converge by Flutter defining bandpass/lowpass filter requirements for each control law release. These changes were then implemented and reflected in a subsequent release of the control laws. The sensitivities of the location of both the rate-gyros and the Nz accelerometer were examined. However, moving the sensors were not required as structural filters in the control laws provided adequate stability margins.

Both open loop and closed-loop ground testing was completed prior to first flight to obtain data that could be correlated with the analysis. Minor tailoring of the filters was required after these tests.

Dynamics

There are two principal focuses with respect to structural dynamics. The first is the definition of the vibration environment to support the design of both airframe structure and equipment installations. The basis of this environment was flight test data acquired during the YF-22 (prototype) flight test program. Large databases of acoustic and acceleration data were assimilated into the Environmental Criteria Document to support detail design. The second focus was the vibration environment to predict and test the high cycle/low cycle fatigue life of structural sub-systems, equipment, tubing, avionics, etc.

Flexible To Rigid Ratios

The flexible to rigid ratios are computed by Loads Department and is forwarded to the Aerodynamics Department for integration with rigid aerodynamics database. These data are used directly by the controls department to generate inputs to the flight simulation model, which in turn is used by Loads to determine maneuvers critical to establishing design loads.

DADT /Stress Allowables

Crack growth analysis was the backbone for establishing durability limits for the aircraft. Parts were designed for 8000 hours of life. Durability Analysis and Damage Tolerance (DADT) established working stress allowables throughout the structure. Point analysis was performed to support MRB (manufacturing rework board) activities using the same databases and techniques established in the basic design.

Detail Design

The major issue in detail design was the enormous pressure to meet allocated weight targets. Continuous trade studies absorbed manpower and schedule resources and as a consequence made the task of getting FEM updated with best if not forward looking data a very low priority task. Since the FEM is the pivotal connection to all facets of generating design to data, the inaccuracies in the FEM had serious impact of the rapid convergence of the design process.

FEM Changes

The process of building a finite element model for a complete vehicle is complex and time varying. Rapid convergence of the model configuration and properties requires the team to look into the future to where the model arrangement and the individual finite element properties will eventually converge. The challenge to be ahead of the actual detailed design is made more complex when three groups in three different companies attempt to operate as a single unit and overcome the different cultures, which by tradition operated as a single unit within each company. Significant organizational tasks were required to assemble a model with many interfaces. This integration task almost becomes an end to itself. What went into the model in so far as material properties, sizing and grid point selections was by its very nature less visible and therefore less likely to be challenged. In the end, the devil was in the details for specification of sizing data, grid point selection, and material properties. Near the end of the design iterations, the biggest variation in internal loads was in FEM property changes and not the external loads.

Typical Processes During Iteration

The basic design iteration was a process that essentially created data sequentially. For example, a FEM was required before basic load process could start. All external loads must be computed before internal loads could be established and loaded into the relational database. All of the internal loads were required before sizing of aircraft parts could start. And finally, the aircraft parts had to be designed before the FEM could be updated. Within this basic design loop, stiffness requirements were established using FEM and mass distributions together with unsteady aerodynamic representations, which in turn were supported by wind tunnel flutter model testing. Stiffness requirements often worked inside the basic design cycle at a rate of 2 or 3 iterations to one full design cycle iteration. The design iteration would not work practically unless each group in the design process worked with models and data that were one or more iterations behind the current cycle. Also, strategic short cuts had to be taken during some of the iterations to get forward looking models and designs to leap frog the full design iteration schedule. Additional short cuts were required when requirements had to be updated to support long lead manufacturing schedules. This required analyst to accept or specially modify what ever the vehicle system analysis maturity was available at that time. In some cases the requirements were limited to only subsystems. The actuator stiffness loop requirements were decided years ahead of the 90% drawing release dates because of the long lead times for the control surface actuator development and testing required for flight. The flight controls development was planned for late software releases because handling qualities was dependent on extensive wind-tunnel testing and the integration of structural flexibility effects into the simulation model from which the processes of control syntheses so heavily depended. But external loads was committed to using maneuvers from the same HQ simulation model to determine in-flight loads as they occurred and not arbitrary maneuvers based on specific criteria such as maximum control surface deflections.

The process flow of specific tasks was more like a quilt than a simultaneous interacting derivation of design to data. Figure 1.0 illustrates the basic interactions and the box show the iteration cycle lags that some of the process-generated data entered into the design. The complete design iteration cycle included external loads to internal loads to design update to the FEM update for the next iteration. The initiation of complete cycle which included fatigue design to data generation was major commitment of program resources. During this major design cycle, there was many timely injection of stiffness requirements. The stiffness and high cycle fatigue requirements often short circuited the outer loop with 2 or more updates within one overall large loads, design and FEM update cycle. Another iteration loop, which operated inside the main loop, was load tailoring. This was particularly true during the last phases of the design development. Load tailoring will probably continue during flight-testing.

Rather than being a well ordered sequence of events, the team injected updated design to data where the leverage to impact the design had the most benefits in terms of the resolving next most critical milestone. In this role, the team interpreted what the program requirements were, and even if a moving target, provided design to data with the best rate of return and still remain within the budget constraints of each IPT/Design to data function support.

Vehicle Level Results

Stiffness Requirements

The control loop actuation stiffness requirements for each of the flight control surfaces namely the rudder, horizontal stabilizer, aileron, flaperon, and the leading edge flap was directly imposed on the IPTs. The definition of how to compute the loop stiffness for each control axis was defined in an Interface Control Document. This metric was used to allow the IPT's to determine the minimum weight design that satisfied the stiffness requirement. Typically, three IPT's were required to determine the stiffness allocation among the main surface, actuator, and control surface. Table 2.0 lists the breakdown in stiffness for each control axis.

Loads Tailoring

With the design drawings basically released to manufacturing, load tailoring via control laws surface scheduling changes provided the tool to keep the existing design within the existing structural capability box while retaining the performance and HQ requirements.

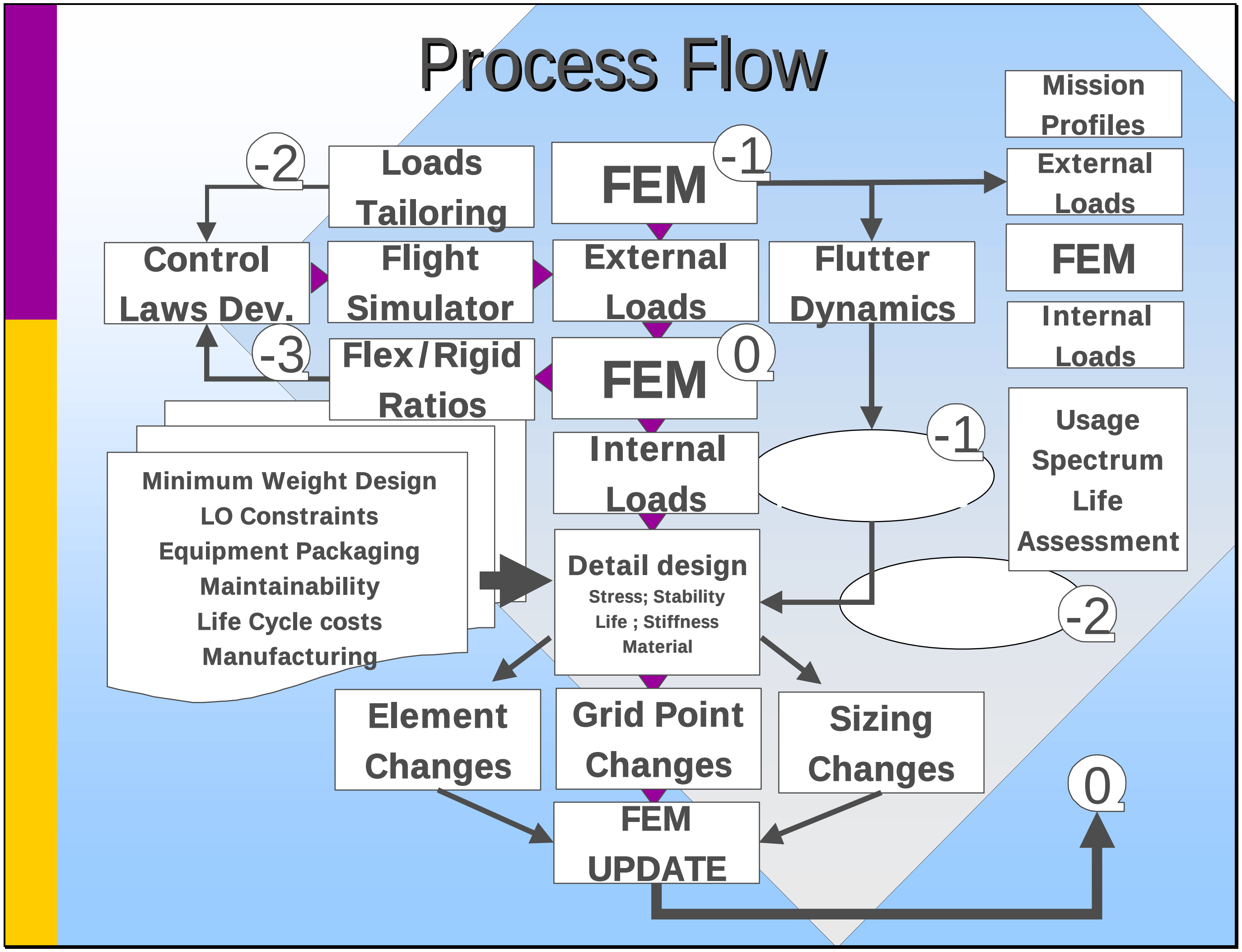
Design To Data

Structure organization provided 90% of the design to data for the F-22. The effective management of internal load data permitted the controlled phased releases of drawings with manageable audit trails. The process provided flexibility when design updates required to release two different airplanes designs known as Block 1 and Block 2. The process kept the airplane design weight within the contract performance specifications.

Design to data as issued from the Flutter organization consisted of defining true design data such as percent changes to physical properties such as cross-sectional area and skin thickness, and composite laminate properties such as the addition of a single ply at a given orientation angle. Figures 4.0 illustrate how data was transmitted to the appropriate Integrated Product Team. The important point here is that the Air Vehicle FEM was used as the vehicle to transmit design to data. This allowed for "checking" the design as to the incorporation of the requirements and for keeping a history of the requirements. Aeroelastic sizing requirements were defined for the horizontal stabilizer skins, vertical fin skins, rudder skins and substructure, flaperon skins, and wing mounted pylons. . Prior to transmission of the design to data coordination and agreement was reached between the functional organization and the IPT that these design changes could be accommodated.

Summary of Important Conclusions

The investment of using a controlled A/V FEM for loads, stress, flutter, dynamics, control law integration, weight estimation, etc., was to a significant measure responsible for the excellent results for stiffness and loads tailoring for minimum weight design while satisfying the airplane performance requirements. The structural design was successfully iterated during four major design cycles. For this type of aircraft, rapid convergence was achieved by: 1) satisfying external load strength and life requirements; 2) then iterate for stiffness and dynamic sizing requirements. These procedures generated critical design to data, which was required by the analyst and designer to provide insight into the available design space and the direction for moving the design. These studies provided data for uncoupling certain design parameters during the design iterations. The large A/V FEM was manageable in terms of configuration control, integration with specific discipline analysis routines, overall tracking, storing, and processing terabytes of data. The recovered cost of using a large model was return many times over by savings in man-hours as compared to decomposition/back transformation approaches. The common basis for communication and changes to the model made the MDO like processes affordable and more to the point, feasible. A very detailed load grid, fuel tank fuel-vapor boundaries matched to maneuver attitude and g loading, and detailed pressure loading were other challenges successfully achieved to satisfy the IPT's requirements. The procedure for modifying flexible panel pressure loads to reflect non-linear wind tunnel pressure distributions especially due to control surface deflections provided a high degree of fidelity to the flexible to rigid ratios and flexible loads calculations. Finally, the computer access for the users drove all the necessary MDO like processes to successfully provide and manage the data across wide area networks, using many types of computing platforms, relational database storage of results for fast and direct answers to questions with real time qualifications.


Process Flow
Mission Profiles
External Loads
FEM
Internal Loads
Usage Spectrum Life Assessment
Loads Tailoring
FEM
-1
-2
Control Laws Dev.
Flight Simulator
External Loads
Flutter Dynamics
-3
Flex/Rigid Ratios
FEM
0
Internal Loads
-1
Minimum Weight Design
LO Constraints
Equipment Packaging
Maintainability
Life Cycle costs
Manufacturing
Detail design
Stress; Stability
Life ; Stiffness
Material
-2
Element Changes
Grid Point Changes
Sizing Changes
FEM UPDATE
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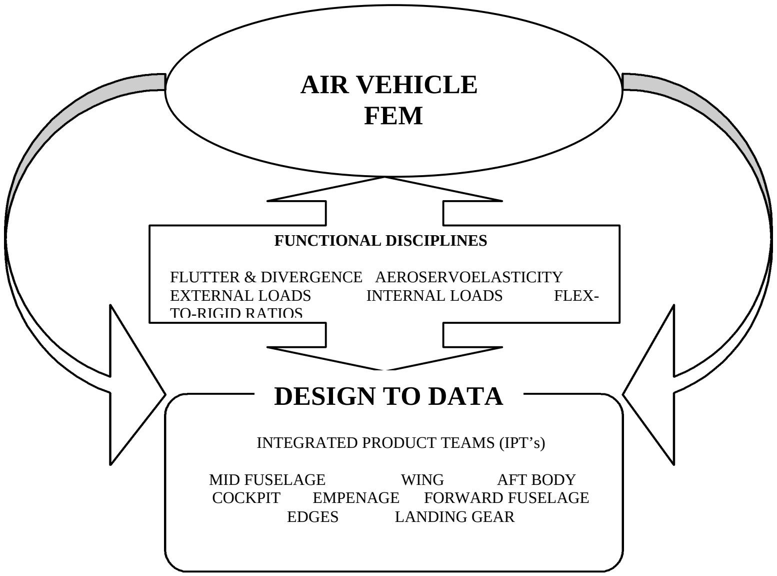

Figure 2 Discipline / IPT / FEM Relationship

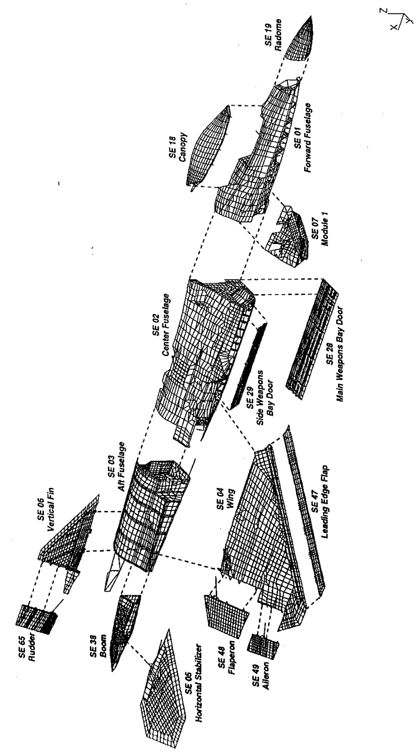

Figure 3 Air Vehicle FEM

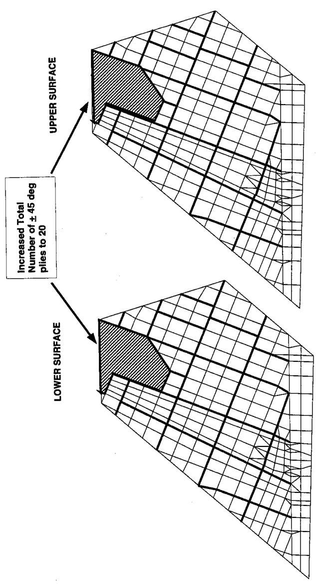

Figure 4 Communicating Design To Data

Surface		Required Loop Stiffness (in-lb/Rad)	Frequency Range (Hz)	Loop Requirement Impact	Allowable Freeplay (Degrees)		Stiffness/ Freeplay Driver
					R.S.S.	At Life	
Stabilizer	Pins	21.4	23 – 30	Weight = 79 Lbs	0.0183	0.060	Classical Flutter
	Bearings				.0270	.069	LCO
Rudder		5.86	27 – 35	Weight =42 Lbs	.0344	.175	Buzz LCO
Flaperon		5.40	21 – 28	Weight = 6.0 Lbs	0.1060	.0300	Classical Flutter LCO
Aileron		1.60	33 – 40	N/A	0.0810	0.274	Buzz LCO
Leading Edge Flap	Actuator # 1	3.58	23 – 30	Number of slices & Backup Stiffness	< 0.82	0.82	Classical Flutter LCO
	Actuator # 2	1.72	30	Backup Stiffness	< 1.21	1.21	LCO
	Actuator # 3	1.46	30	Backup Stiffness	< 1.21	1.38	LCO
	Actuator # 4	1.41	30	Backup Stiffness	< 1.38	1.38	LCO
	Actuator # 5	1.29	30	Backup Stiffness	< 1.38	1.38	LCO
Fin		See Rudder	N/A	Weight = 60 Lb.	N/A		See Rudder

Table 1.0 Loop Stiffness Impact & Freeplay Requirements

Surface	Type	Quantity
Rudder	Skins	118
	Spars	6
	Ribs	6
Vertical Fin	Skins	138
	Spars	10
	Ribs	5
Flaperon	Skins	132
Aileron	Skins	72
Tail boom	Skins	19
Horizontal Stabilizer	Skins	162
	Spar	15
Wing	Skins	195
	Spars	8
Total = 886		

Table 2.0 Design Variable Distribution