MSC NASTRAN AEROELASTICITY FOR AIRCRAFT CERTIFICATION

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SUMMARY

MSC Nastran is an industry-leading tool for aeroelastic analysis for aircraft design and certification for loads, dynamics, and flutter. These analyses are used in all parts of the design process, from conceptual design to final certification and fleet support.

This paper focuses on the use of MSC Nastran for certification level analysis. Specific examples of MSC Nastran/Patran and related tool usage are shown for real world certification projects to demonstrate the ability of these tools and procedures to provide critical certification data at the highest required levels of fidelity (FAA and international). Analysis types and levels of detail are also summarized for earlier steps of the design cycle.

KEYWORDS

MSC Nastran, Aeroelasticity, Flight Loads, Flutter, Certification, Design.
1: Introduction

Modern aircraft are designed to exacting airworthiness standards imposed by national or supranational agencies such as the FAA and EASA. Meeting these requirements requires a simulation capability that is flexible enough to allow multiple standards of fidelity and inputs, but also model complex aerostructural interactions to high accuracy. MSC Nastran provides this capability through the core FEM solver coupled with the capable doublet lattice model, the multiple methods of data entry and calibration, and the options for data tracking and output.

TLG Aerospace, LLC (TLG) uses the MSC Nastran solver as the core of their aeroservoelastic capability for new and modified aircraft and related aerospace products. Typical projects are for OEMs, third-party modifiers, and other companies which design, analyze, build and sell aircraft, aircraft modifications, and related products.

This paper focuses on the use of MSC Nastran for design and certification level analysis. Specific examples of MSC Nastran/Patran and related tool usage are shown for real world certification projects to demonstrate the ability of these tools and procedures to provide critical certification data at the highest required levels of fidelity (FAA and international). Analysis types and levels of detail are also summarized for earlier steps of the design cycle.

2: Airworthiness Requirements

Airworthiness requirements are specified and maintained by national and international agencies to provide safety and oversight for the aviation industry. These requirements govern all aspects of air vehicle design, construction, operation, and maintenance.

Requirements for structural strength of airplanes are specified in terms of operational requirements and margins of safety. The regulations specify flight and ground conditions including maneuvers, gust encounters, hard landings, and taxiing over rough surfaces. The airplane manufacturer must show through analysis that the airplane maintains safe structural margins for all of these conditions for nominal operations and for specified assumed failures of structural members and equipment. Compliance with the regulations is shown by analysis. Sufficient flight and ground testing is required to validate the analysis and results.
For structural strength, a specified safety factor for the applied load is required. Most cases require a safety factor of 1.5 (structure must be designed to 150% of the calculated load). Some failure conditions and specific criteria cases specify other safety factors. For aeroelastic stability (flutter) the safety factor is applied to speed, and the airplane must be analyzed and tested to higher speeds than are allowed in regular commercial or private service.

3: Aircraft Loads Analysis

Aircraft loads are the forces and moments applied to the airplane structural components to establish the required strength level of the complete airplane. These loadings are caused by air pressure, inertia forces or ground reactions during take offs and landings. Determining design loads involves a full aircraft analysis of the air and inertia forces during the prescribed flight or ground maneuvers.

![Symmetric Maneuvering Flight](image_url)

Aircraft loads are needed at all design phases, from day one through certification and product lifecycle support. Early in preliminary design, structural designers need initial loads to size preliminary structure. As the design iterations progress, the detail and fidelity of the loads increases. The final step for an aircraft is a full set of certification loads for submission to governmental agencies such as the FAA and European Aviation Safety Agency (EASA).

The loads analysis needs to cover all possible combinations of flight and ground condition parameters such as speed, altitude, flap angle, airplane gross weight, airplane center of gravity, passenger and payload distribution, fuel quantities, engine thrust and airbrake positions for each of the required maneuver and load cases for each part of the airplane. Static loads are
calculated for conditions in which the aircraft is assumed to be at steady state and range from high speed dives to low speed stalls. The dynamic loads are a result of how the airplane responds in unsteady conditions such as gusts, turbulence, control surface oscillations, engine failures, landing, and taxi.

The input data to the loads analyses are accurate airplane geometry, aerodynamic data, weight (inertia) data, design speeds, stiffness data, miscellaneous systems data, operational data and regulations and requirements. This makes loads a multidisciplinary process. Early in a design program, these parameters can be estimated from various methods. As the design becomes more detailed and defined, the inputs will be more refined, and for the final certification level, verified by test.

4: Aircraft Flutter Analysis

Flutter is an aeroservoelastic phenomenon in which unsteady aerodynamic forces combine with structural vibrations to produce a self-feeding oscillation which are dangerous if unstable. Flutter analysis is performed to ensure that the aircraft is safe and free from flutter at all points in the flight envelope. The interaction between structural vibrations and unsteady aerodynamics are modelled to show whether an airplane will respond in a stable or unstable fashion to atmospheric or other disturbances.

The FAA, EASA and other agencies require that the aircraft is shown to be free from flutter for all nominal flight conditions and for critical combinations of failed systems and structures. All possible combinations of fuel, payload and operating conditions must be considered. Flight flutter tests must be performed
for some of the conditions to demonstrate the accuracy of the analysis and to prove the airplane is safe to operate.

5: Certification and the Aircraft Design Cycle

Aircraft structural, aerodynamic, weight, performance, and certification requirements are dependent on each other. For this reason design, development, and certification is an iterative process.

*Figure 2: Aircraft Design Cycle.*

The design starts with Design Requirements and Objectives (DRO). Along with size, performance and weights, the DRO includes cost objectives and certification requirements. Engineers work from the DRO to create the initial airplane configuration.

Once an initial configuration is defined, the first design cycle begins. Estimates and approximations for input data are required - the aerodynamic analysis needs structure and weights design data, structural design requires loads data, and the loads analysis uses aerodynamic, structural, and weight data. After the initial design process, the results are compared against the objectives, assumptions and data are revisited, and an updated design is created. This
process continues throughout the design, development, and certification process. Initial design phases involve numerous, relatively short design cycles as the configuration evolves to meet requirements. Later design phases are longer and involve higher fidelity data and more complicated analyses. The cycle continues through the project certification, as the certification loads depend on ground and flight test validation of the final dataset.

Aircraft programs typically have 4 major development cycles for structural strength. These cycles may have sub-cycles for particular data updates or trade studies. At each stage of development the data fidelity and calculation requirements increase. In this paper the structural loads and strength cycles are referred to as ‘Product Development’, ‘Preliminary Design’, ‘Design-to’, ‘Certification’. These are common names for these levels of fidelity and analysis but other names are used. Some companies number the cycles and sub-cycles (Loads Loop 1.0, 2.0, 2.1, etc).

6: Product Development Cycle

Product development represents the initial cycles of aircraft design. Product development cycles are used to explore the design space and evaluate different (sometimes radically different) concepts. Important features of this design cycle are rapid turnaround and overall product scoping. Typically highly automated and statistical methods are used to minimize the requirements to develop input datasets.

Aerodynamic data are often taken directly from doublet lattice or similar aerodynamic theories with little or no calibrations. Structures are modelled as idealized beams. Mass properties have coarse distributions.
The loads and flutter conditions are typically a small subset of the eventual certification dataset. The cases are selected based and past experience with similar designs and simple predictions of overall critical parameters. The number of cases considered will usually be in the tens or hundreds. For unusual or novel configurations the dataset may need to be expanded even at this level to ensure the driving conditions are found.

The results are used for initial structural sizing, feasibility checks, and trade studies of different structural concepts.

7: Preliminary Design Cycle

Preliminary Design is the typical name for the initial design development. In this phase the basic airplane configuration and overall parameters have been selected. The goal of this phase is to “bound the envelope”; i.e. to increase the fidelity to point where overall trends and sensitivities can be identified.

Aerodynamic data are often taken from CFD calculations, sometimes augmented by wind tunnel data. Structural data will still be mostly idealized but with higher fidelity and often full FEM modelling of critical structure.

A greater number of conditions will be selected for analysis. The number of speed/altitude combination is typically increased, as is the number of payload and fuel conditions. Additional sweeps and sensitivities will be run to identify critical behaviour and conditions. Typically several hundred individual loading conditions are considered at this stage.
8: ‘Design-to’ Cycle

The ‘Design-to’ cycle receives its name because these are the data which will be used for the final airplane design. The full certification dataset will not be available until after the airplane (or at least critical components) have been built. For this reason the airplane structure will actually be designed and built to the ‘design-to’ loads and flutter requirements.

This places an increased fidelity requirement on the dataset while still requiring that the results are a conservatively safe airplane. Theoretical aerodynamic data will be augmented by experimental results from wind tunnel tests and possible flight tests on earlier vehicles. For novel or unusual configurations some level of prototyping may be used. The aerodynamic calculations will be a combination of scaled doublet lattice and direct pressure inputs on the lattice mesh or directly on the CFD mesh.

Structural modelling will be updated to the best possible estimates and greater use will be made of higher fidelity FEM models with finer grids. Reduced order modelling may be used to reduce the degrees of freedom to a more manageable level.
A large matrix of cases will be used establish the critical loads and flutter conditions, with individual conditions numbering in the thousands or tens of thousands. Because these loads will design the structure it is important to find all critical conditions at this stage so that the important design cases are considered in the analysis. Any conditions that are not considered must be expected not to be critical on the basis of sensitivity studies or past experience.

9: Certification Cycle

Certification data have the highest requirements for fidelity and comprehensiveness. For certification the airworthiness authorities must be presented with acceptable evidence that all required conditions have been considered and that the resulting data are accurate or conservative. For structural strength and aeroelastic stability ground and flight test validation is required.
The structural strength and aeroelastic stability calculations must be made for all required flight and ground conditions, all payload and fuel loading combinations, and all combinations of nominal and failed structure and system conditions, such as:

- Static aeroelastic structural response and loads for flight maneuvers including 1g cruise, maneuvering in pitch, roll, and yaw, and static ground conditions.
- Dynamic airframe response to gust and turbulence encounters
- Effects of control systems such as autopilots, yaw dampers, Mach trim, and modern fly-by-wire flight computers
- Effects of single and multiple structural and system failures on static and dynamic response and strength

For transport category airplanes these requirements typically lead to tens of thousands of individual conditions.

10: Validation
FAA requires that structural aerodynamic and inertia loads be calculated in a rational fashion and ‘accurately or conservatively’ represented. Validation must be provided by test. It is important to note that the certification is by analysis and the validation is by test. The critical flight loads are not usually validated by test, i.e. the airplane is not flight tested to critical loading conditions. A flight loads survey is performed at lower load level conditions and these results are used to validate the analysis. Usually the conditions are selected at 80% of limit load (load factors of 2.0 compared to 2.5, etc).

For loads validation, the predicted loads must be accurate or conservative compared to the analyzed loads. For an efficient structure the most accurate loads are desired. Typical expectation is for the critical loads to be predicted to within a few percent or less. This places a demand for high fidelity in the aerodynamic, structural, and mass data which are used in the final calculations.

Aeroelastic stability is also validated by test. These tests are carried out to a flight design dive speed (VDF) which is higher than the maximum operating speed in service. The speed margin is selected to provide a sufficient margin of safety in operation to protect against accidental overspeed or upset events. The analytical clearance must be made to a higher speed yet, currently 1.15VDF. This provides a margin of safety for the test flights themselves.

![Figure 7: Example Flutter Clearance Envelope.](image)

For flight conditions with failed systems or structure the philosophy is the same but the required speed margins are different. Some failure conditions may be
validates in flight test but structural failure conditions are not tested for safety reasons.

Figure 8: Flutter Clearance Flight Test Data.

11: MSC Nastran Aeroelastic Capabilities for Certification

MSC Nastran solution sequences SOL144, 145, and 146 are well-suited for these calculations, which require both structural and aerodynamic capabilities. FAA and similar authorities require that ‘if deflection under load significantly changes the load distribution, this must be taken into account’. For large airplanes with swept flexible wings the aeroelastic effects are important and must be calculated using a coupled aeroelastic solver. Smaller straightwing airplanes may often be treated as rigid structure but this must be determined and demonstrated on a case-by-case basis.

The loads and flutter calculations for certification place a high demand for accuracy and for the ability to input and use test and theoretical data from other sources. The accuracy requirements drive needs for aerodynamic data correction and inputs, arbitrary control of static aeroelastic trim conditions, output quantity definition, and database development and maintenance.

MSC Nastran contains many features, enhancements and upgrades that directly address these needs. These features include:

Aerodynamic data input. Aerodynamic pressures may be calculated from the built-in doublet lattice solver or alternatively input directly as pressures or forces on structural grid points. All of these aerodynamic variables may be
linked to control variables and used in the airplane force balance for flight maneuver conditions. This capability allows TLG to input real-world data directly into the model, even if the results are difficult to calculate with the industry standard doublet lattice model. Examples include engine thrust, aerodynamic effects of deployed spoilers, and high trailing edge flap deflections.

User-defined input variables. MSC Nastran allows arbitrary combinations of user-defined inputs to be used as part of the balanced airplane calculations. These inputs can control arbitrary pressure inputs as mentioned above, or existing MSC Nastran trim variables, or combinations of existing variables. This functionality allows TLG to perform such tasks as balancing the airplane in any way needed for particular calculations, defining control surface relationships such as control wheel to aileron gearing, or linking any set of balance variables together.

Separate rigid and flexible mesh. A single aeroelastic trim calculation can be performed using one aerodynamic mesh for the rigid aerodynamics and second aerodynamic mesh for the flexible increment. TLG uses this capability to maintain total control over the aerodynamic data.

Monitor points. Loads calculations require complete user control over how the aerodynamic and inertial loads are tracked and accounted for in the downstream output. Structural FEM and aerodynamic mesh elements do not inherently provide this level of control. The aerodynamic and structural monitor point capability in MSC Nastran allows definition of engineering-level loads summations to sort for critical conditions and to provide loads to stress engineers.

12: Conclusion

Modern commercial aviation has the best safety of practically any transportation system in history. This is largely due to a high standard of strength and stability requirements placed on the structural design by the FAA, EASA, and other airworthiness authorities worldwide. Designing and showing compliance to this high standard requires a simulation capability that is flexible enough to allow multiple standards of fidelity and inputs, but also model complex aerostructural interactions to high accuracy. MSC Nastran provides this capability through the core FEM solver coupled with the capable doublet lattice model, the multiple methods of data entry and calibration, and the options for data tracking and output.