Virtual Prototyping of a Transit Bus to Predict Service Life

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Abstract

Designing robust vehicles with low maintenance costs is a common concern among automotive manufacturers. Maintenance concerns most often arise when discrepancies exist between the actual and expected service life of vehicle components. Minimizing these discrepancies, and the associated maintenance costs, is the primary focus of durability analysis within the automotive industry. As companies shift toward shorter development cycles, durability analysis tools and processes must be implemented earlier within the development process. This trend encourages the integration of durability analysis with existing design and analysis software packages.

Successful service life estimates require accurate knowledge of the dynamic stresses a component is likely to encounter. To acquire this information for each component, one must have a precise representation of both the component interactions and the external vehicle loads, and the ability to extract the corresponding local stresses. Through the combination of ADAMS (multi-body simulation) and ANSYS (finite element analysis) Mechanical Dynamics has successfully integrated this process within the latest design from Orion Bus.

A primary goal of Orion Bus analysis was to predict bus service life numerically, based on virtual prototypes of the proposed bus design. This goal was realized through a cooperative effort which integrated the following steps:

- Parallel construction of the suspension and steering systems within ADAMS and the bus structure within ANSYS and Pro/Engineer.
- Analysis of ADAMS models through suspension system metrics to validate the design against accepted criteria. Structural analysis of the ANSYS model to ensure acceptable design and structural integrity.
- Cooperation with Bodycote to define an appropriate mission profile for implementation on an ADAMS-based four post shaker.
- Execution of the shaker test simulation for an assembled virtual bus prototype under various loading conditions.
- Analysis of structural stress within the vehicle, and corresponding life prediction calculations (rainflow count and Miner's rule damage calculation).
- Reporting of the analysis results, and recommendations for design modification
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Process

ADAMS model of bus suspension and steering system

Comparisons of OrionVII to OrionV and OrionVI

The construction of a virtual prototype for the Orion VII required the integration of several existing technologies. The resultant model drew upon both ADAMS-based suspension and steering design tools, and Pro Engineer/ANSYS structural design techniques. The resultant model achieved a degree of functionality that enabled both full vehicle event simulation and stress-based durability analysis. Extensive analysis of the previous Orion V and Orion VI bus designs encouraged confidence in the results of the Orion VII simulations.

The design concepts for the front suspension and steering system of the Orion VII were similar to those of the Orion VI, yet the rear suspension design was more closely related to the Orion V. Consequently, in addition to creating ADAMS models of the proposed Orion VII designs, models corresponding to the front of the Orion VI, and the entire Orion V were created for comparison purposes.

During the Orion VII design analysis, the previous bus benchmarks provided valuable insights, as well as a natural context for discussion of the behavior of the new bus. This ongoing discussion allowed early comparative feedback on preliminary steering and suspension designs.

Front suspension, Rear Suspension, Steering System, Powertrain

ADAMS models were built of the bus front suspension, rear suspension, steering system and powertrain. ADAMS/Pre was used to quickly build and simulate the various suspensions. The Orion VII bus design included a solid axle front suspension with air springs, and a standard four link suspension. A panhard rod was used to control lateral movement of the axle. The OrionVII rear suspension had dual rear tires, as well as a solid axle rigidly attached to a "walking beam"; four air springs and four shocks connected the walking beam to the frame of the bus.

Analysis of suspension behavior

Prior to building a full vehicle model, it was vital to understand the design of the suspension subsystems. Therefore, front suspension, rear suspension, steering system, and powertrain analysis was performed on the vehicle.

Suspension kinematics

Once the suspension model had been built up in ADAMS, the model was simulated to determine the suspension kinematics. The suspension was put on a virtual test bench, and exercised in parallel wheel travel (ride motion) and opposite wheel travel (roll motion). Metrics such as toe, caster, camber, longitudinal wheel recession, and lateral wheel recession were plotted as a function of wheel travel. Targets for each of these metrics was determined by Mechanical Dynamics using industry standards, as well as comparisons to previous bus designs (Orion V and Orion VI). The suspension geometry was modified until superior suspension kinematics were attained.

The steering kinematics were also simulated using a virtual test bench for the steering system. The steering system was articulated to maximum road wheel travel (bounded by structural clearance of the wheel wells). Steering ratio, steering ackermann, and steering uniformity (left to right) were observed and optimized in this phase of the analysis.

The powertrain was analyzed to determine driveline plunge and u-joint angles. Because of the relatively short drive shafts, articulating over large suspension travel, it was important to monitor the amount of driveshaft plunge.

Suspension compliance

After the kinematics of the suspension were analyzed and well understood, suspension compliance values were examined. The suspension was put on a virtual test fixture and forces were applied to the wheel center and contact patch. Displacements were measured in the various directions to get an understanding of the suspension force vs. deflection characteristics. The bushing, air spring, and anti-roll bar attributes were modified until good suspension kinematics were attained.

Suspension load cases

To support the initial design of the frame, static load case simulations were performed on the front and rear suspension. The static load case analysis helped the design and FEA engineers some information about the amount of loading going into the vehicle structure when the road wheels are loaded.

Analysis of full vehicle behavior

Ride and handling events

After the front suspension, steering system, and rear suspensions were designed and analyzed, the suspension subsystems were combined with both rigid and flexible frame models to produce a full vehicle system for analysis. For the majority of the analyses, the vehicle was trimmed to the gross vehicle weight (GVW), although both unloaded (no passengers or cargo), and fully loaded (typical passenger and cargo) configurations were also tested.

The following ride and handling events were run on the full vehicle model, listed with metrics associated with each event:

- Altoona Lane Change: animation and tire vertical force
- Tilt Table Test: rollover propensity
- Swept Steer: steering behavior
- Constant Radius: over/understeer budget
- Step Steer: roll and yaw overshoot numbers
- Brake Drift: lateral drift under braking
- Steady-State Drift: lateral drift with steering wheel free

Durability events

Orion Bus has a history of testing new bus designs at the Altoona test track in Altoona, Pennsylvania. The various Altoona durability tracks were implemented in the Orion VII ADAMS model, and the Orion VII bus was driven over the test tracks to determine the suspension loading over the various obstacles. The Altoona tracks that were simulated in ADAMS are:

- Track 1: 1" Random Chuckholes
- Track 2: 3/4" Chatter Bumps
- Track 3: High Crown Intersection
- Track 4: Frame Twist Event
- Track 5: Railroad Crossing
- Track 6: 4" Chuckhole

The loads generated by the bus driving over each of the Altoona test tracks were examined and used to re-run the static load cases. One of the challenges of the Orion VII modeling was determining a "typical" load case to use in the static load case analysis. The Altoona Test Track analysis verified the static load case assumptions, as well as providing dynamic load information for the frame design team.

Build ANSYS model of bus body structure

Design work done with Pro/Engineer

The primary CAD tool in use at Orion was Pro/Engineer. At the outset of the Orion VII project, the basic geometry of the bus was available in Pro/Engineer format. Building upon the rough geometry, Mechanical Dynamics was able to generate additional Pro/Engineer geometry that was used as the framework for a finite element model. The Pro/Mesh module of Pro/Engineer had the ability to generate a finite element model directly utilizing the 3D CAD geometry. With a finite element model built on the fully parametric

CAD geometry in Pro/Engineer, it was possible to make changes to the CAD geometry and then have a new version of the finite element model immediately available. The ability to quickly regenerate the finite element model to reflect changes in the bus geometry allowed many iterations of design concepts to be investigated in a relatively short timeframe.

ANSYS analysis of bus structure

The Association of Public Transit Authorities (APTA) compiled guidelines that aided in the design of transit buses. Ultimate strength criteria for cases such as towing, hoisting, crashworthiness, and rollover are described. These guidelines, although quite thorough, do not describe durability requirements for the service life of transit buses.

Using their extensive experience in the durability testing of vehicles, particularly transit buses, Bodycote had developed durability criteria that are general in nature, but sufficient to assist in identifying the potential durability problems of a transit bus. Bodycote had determined allowable stress levels for simple static load cases that provided adequate durability for 500,000 miles of heavy duty service, such as in New York or Chicago. Having criteria that were simple and easy to apply at the start of a design effort was important in evaluating the effect of design modifications. Additionally, well documented design criteria provided a target for optimization. The early stages of bus frame design were characterized by numerous changes in the structural layout. These arose due to many factors including geometry changes, manufacturing limitations, and strength requirements. It was imperative that the analyst was able to evaluate these changes in a timely manner. The notion that a full durability analysis could be performed on a recurring basis, for each design iteration, is a falsehood with present day technology.

The durability criteria for the transit bus were deceptively simple: 1.0 G accelerations in the vertical, fore/aft, and lateral directions, each with their own allowable stress levels. Any stresses that exceeded these allowable levels indicated a potential durability problem. Problem areas could be immediately identified using ANSYS, and redesigned in Pro/Engineer to strengthen the structure. For areas where the durability cases did not indicate problems, the design could have been governed by other criteria such as towing, roof crush, side crash or overall bus stiffness.

Eventually a design emerged that best satisfied all of the strength criteria while still fulfilling its functional requirements.

Four post shaker test

Build ADAMS model of four post shaker fixture

Orion Bus Industries has had several busses tested on a physical test shaker as part of their bus development process. The physical four post shaker test gave the bus development engineers a chance to put a design prototype through an accelerated durability test in a controlled laboratory environment, ideally confirming that the design was sufficiently durable. However, should the four post shaker event illuminate structural design problems, it was often difficult and costly to react to this information before the bus went into production. The goal of the virtual test shaker was to conduct durability testing earlier in the design process, thereby reducing the degree of physical testing and giving the Orion development engineers more time to react. Hence, this approach should reduce both the testing cost and the risk associated with prototype failure.

An ADAM S model of the shaker test was developed which allowed independent motions to be specified at either the bus spindles or the contact patches of the tires. This allowed the shaker to replicate tests based on both road profiles and measured spindle accelerations. The accuracy of the resultant simulations was verified using measured data from the durability testing of the Orion V.

Definition of drive files to simulate service life

The most critical element of the virtual four post shaker testing was the drive file development. The drive file provided motion signals for each of the four shaker pads, ultimately determining the motion of the entire bus. In the past, the drive file had typically been determined through the testing of physical prototypes. For both the Orion V and Orion VI busses, one of the more severe New York City routes was used as the basis for the durability drive files. Measurements taken while driving this route were examined, and reduced to a smaller motion profile that was representative of the route and could be implemented on the physical shaker test fixture. Examination of these drive files, as well as data from typical bus service allowed the bus development engineers to determine the equivalent miles of service life associated with each drive file. The drive file was then repeated as necessary to approximate the desired service life. For the Orion VII analysis, a service life of 500,000 miles of was desired.

One of the challenges of the Orion VII analysis was the development of the drive file without the opportunity for physical testing. The process of developing a drive file for the Orion VII started with an analysis of the Orion V and Orion VI durability tests. The drive files from these tests were based primarily on data gathered while driving over cobblestones. A corresponding road profile was developed for the Orion VII using white noise that was band-limited between 2 and 15 Hz. Separate profiles were generated for the curb and road sides (left and right sides) of the bus and a front to rear phase delay was added to simulate a bus speed of 30 miles per hour. Finally, the signal amplitudes were adjusted to achieve RMS axle accelerations similar in magnitude to those measured in the Orion V and Orion VI durability tests. As a verification of the drive file, it was applied to the Orion V model, and the RMS acceleration values were found to be appropriate.

Life prediction analysis

Stress histories taken from ADAMS model

Performed analysis of stress histories

Recently developed custom tools within ADAMS, developed by the Mechanical Dynamics Itallia, allowed the extraction of the complete displacement set for every node in the finite element model, at each time step in an ADAMS simulation. These displacement sets were used as input cases in ANSYS and accordingly the stress time history were calculated. The stress/time history at any location could then be compiled by extracting the appropriate stress for each time step. The selection of locations for time history extraction and fatigue analysis was based in part on the results of the static durability cases, but also on the results of the modal analysis. If a particular mode contributed significantly to the strain energy in the ADAMS simulation, potential problem areas that were not caught by the static durability analysis were illuminated.

Peak-Valley Extraction and Rainflow Cycle Count

For each of the locations on the bus body structure that were identified for fatigue analysis (for example, points around the windows or close to the suspension attachments), the stress time histories were analyzed. The fully populated stress time history contained a large amount of data (perhaps 90%) that was not pertinent to the fatigue analysis. The pertinent data was those stress levels where the stress changed from an increasing value to decreasing value (or vice versa). These stress reversal points, commonly called peaks and valleys, were saved for analysis. All of the data between one stress reversal point and the next was superfluous for the linear fatigue analysis and was discarded.

Following the extraction of reversal points from the stress/time history, the rainflow cycle counting routine was used to extract stress cycles that fully described the stress/time history. The routine filtered through the peak and valley points and paired up the highest peak with the lowest valley. This process was repeated for the remaining reversal points until each peak was paired with a valley. The result was a spectrum of stress cycles.

Results

Results to be discussed in presentation.