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Title
A FINITE ELEMENT VEHICLE ANALYSIS LIBRARY FOR COMMERCIAL VEHICLES

Abstract
MSC/NASTRAN is one of the general purpose finite element programs used at DAF Trucks N.V. Performing a finite element analysis of a commercial vehicle may be time consuming for two reasons. Firstly, many variations in vehicle specification exist, due to customer request. Secondly, the investigation of the static and dynamic behaviour of commercial vehicles often requires a full vehicle model. The resulting large numerical model has typically several hundred thousand degrees of freedom.
In order to perform the requested static and dynamic analysis *on time*, DAF Trucks N.V. applies component mode synthesis and automatically assembles a full vehicle model from a vehicle analysis library.
This paper addresses some aspects of the vehicle analysis library and shows examples of a full vehicle model used for static and dynamic analysis. The dynamic analysis example shows how frequency response functions, calculated with MSC/NASTRAN, are post-processed with the aid of a toolbox. This toolbox enables fast evaluation of e.g. ride comfort and load spectra for a variety of operating conditions. Furthermore, online sensitivity or optimisation studies are possible.

1. Introduction

The modern design process of the load bearing structure of commercial vehicles requires a very careful analysis of their static and dynamic properties. At least two classes of problems should be considered: (quasi-)static manoeuvres and vibration analysis. DAF Trucks N.V. utilises MSC/NASTRAN to tackle such problems. Furthermore, DAF focuses on conducting FEM analysis as early in the design process as possible.
DAF Trucks designs and produces a variety of commercial vehicles depending on customer's transportation applications within the framework of pending legislation (masses and dimensions, sound levels, safety, emissions etc.). The vehicle lay-out is often a trade-off in utilising the available volume.

One difficulty experienced by commercial vehicle designers is the problem, that in most cases a full vehicle model (see Figure 1) is necessary for conducting (quasi-)static, fatigue and ride-comfort analysis in the frequency domain between 0-20 Hz. 'Heavy' components like a fuel tank or a battery box fixed to the sides of the chassis frame not only make the structure non-symmetric, they also produce non-symmetric dynamic loading. Furthermore, these components are often themselves the subjects for static or fatigue analysis. Typically, the resulting full vehicle FEM model can have as many as 600.000 dof.

Figure 1 Full vehicle FEM model.

On the other hand many different vehicle configurations exist. Commercial vehicles are assembled from a number of components: chassis frame, engine, cabin, axles etc., which exist in great diversity. Within a single product family, multiple wheelbases and axle configurations are common practice. This has far-reaching consequences for e.g. the chassis frame, which is of a ladder type, built up out of two longitudinal or side members and four to ten cross members. Detailed analysis is often necessary for several vehicle configurations.

The assembly and solving of a variety of such 'large' FEM models can be very time-consuming and expensive. Therefore, the following goal was defined:

1. Perform static and dynamic design sensitivity and optimisation analyses on a single vehicle model.
2. This vehicle model should have 'low' computational costs when performing frequency response calculations.
3. Assembly time of the vehicle model should be kept to a minimum.
4. The vehicle component models should be made accessible to several users.

2. Structural vehicle analysis

2.1 Overview

The solution shown in this paper, divides the complete MSC/NASTRAN analysis into three distinct phases (see Figure 2). Furthermore, we assume that certain components will be reduced, and other components will not be reduced, based on an understanding of the structure (the problem areas and investigation aspects are often known beforehand) and expectations for change. In our case we discriminate for chassis frame components and the cabin. All components in the chassis frame: side members, cross members, battery box, fuel tank, exhaust silencer and spare wheel winch are reduced with static condensation. The cabin structure is reduced with Component Mode Synthesis (CMS).

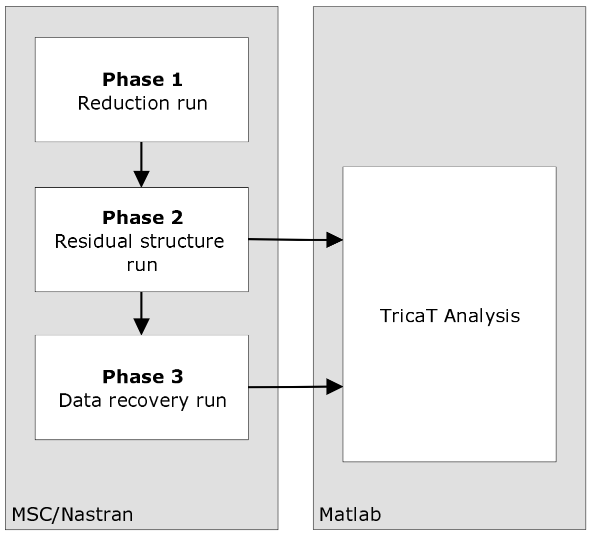

Figure 2 Global overview of structural vehicle analysis.

Phase 1 is the reduction run for each chassis frame component. Phase 2 is the assembly and solving of the residual structure. Phase 3 is the data recovery run. The creation of the three runs is automated with an in-house developed FORTRAN programme. The results of static and normal mode analyses are post-processed in a regular manner.

In case of dynamic analysis in the frequency domain, the MSC/NASTRAN output file contains a set of frequency response functions (FRF's). These FRF's are subsequently post-processed in a Matlab[1] environment (see Figure 2) with the aid of a unique toolbox called TricaT (Toolkit for Ride Comfort Analysis of Trucks). The basic task of TricaT is adding real dynamic inputs, depending on vehicle velocity and road type and calculating and postprocessing the output.

2.2 Vehicle analysis library

Figure 3 shows the three phases of the vehicle analysis library in more detail. The grey boxes indicate the automated creation of the separate runs.

Phase 1

In phase 1 a detailed FEM model is created for each individual component. The creation of the reduction run for the chassis frame components has been automated. For the creation of the

[1] Matlab is a registered trademark of The MathWorks, Inc.

run, additional reduction data are necessary (This data are compatible with MSC/NASTRAN and MSC/PATRAN). Typically, these data will contain: definition of boundary (A-set) grids, type of component, etc. The created reduction run is a standard SOL103 without any DMAP. The reduction method for these components is Guyan reduction, which is approximate for mass and damping in dynamic analysis. Obviously, this may be improved by using component modal synthesis (CMS). For the chassis frame, which is a highly coupled structure with all coupling points in the A-set, omitting additional generalised co-ordinates is permitted without noticeable loss of accuracy.

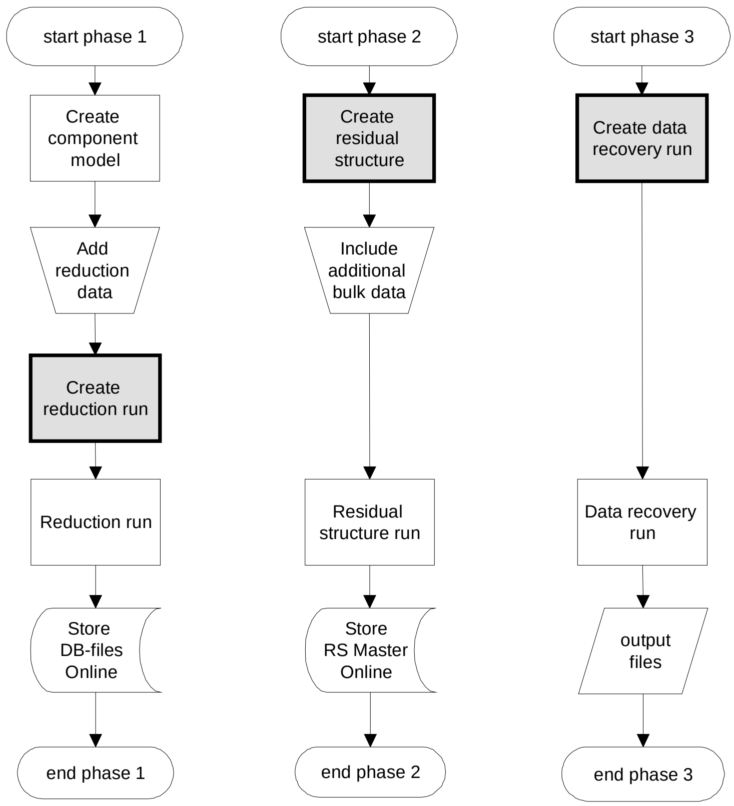

Figure 3 Three phases of vehicle analysis library: 1) Reduction, 2) Assembly and solving of residual structure, 3) Data recovery. Grey boxes denote automatically created runs.

The ‘split database technique’ is used in order to reduce the size of the database file [2]. In this case the database file is split up into a .DBDN (downstream) and a .DBALL (upstream). This is enabled via the location PARAMETER, DBDN.
The database files are stored online. The .DBDN and .MASTER dbsets are needed for the residual structure run (phase 2) and the .DBALL dbset is only necessary for data recovery (phase 3). The .DBDN file contains the datablocks KAA, K4AA, KTT and MAA.

The cabin structure is also reduced (free-free) in a separate run, whereby the reduced mass, stiffness and damping matrices (M2GG, K2GG, B2GG) have been written in DMIG format. Typically, the reduced cabin structure has approx. 20 boundary grid points plus 10 generalised co-ordinates.

Phase 2

When all components of the chassis frame are reduced, the assembly run is created. First all boundary grids are automatically renumbered. Subsequently, all superelements are created as external images (CSUPER cards). The resulting residual structure contains:

- ASSIGN statements to multiple .MASTER dbsets of the reduced components.
- DBLOCATE statements for datablocks in .DBDN dbset.
- A full set of renumbered boundary GRID points.
- CSUPER bulk data entries for the external superelements.
- Coupling elements (CBAR) between the external superelements.

This method enables the possibility of relocating and duplicating components. So far, the automatically created residual structure comprises only of the chassis frame (see Figure 4).

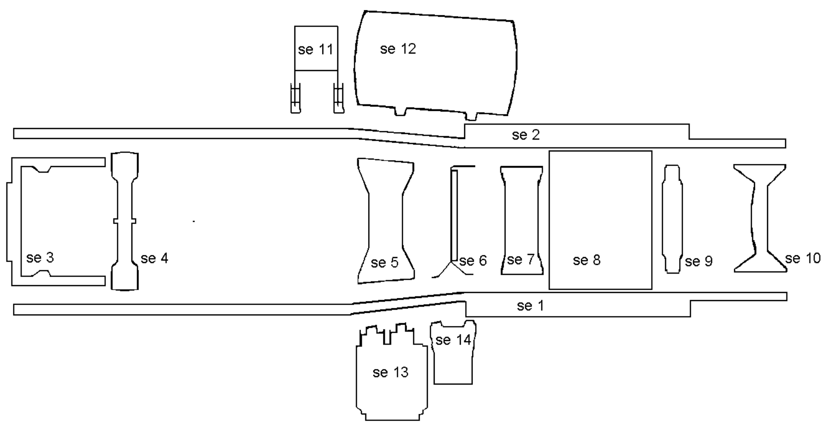

Figure 4 Exploded view of assembled chassis frame.

The next step is to include additional bulk data for engine, axles, reduced cabin and trailer. All suspension components are kept in the residual structure. The residual structure contains approx. 5000 dof. Runs such as SOL 101, SOL 103 and SOL 108 can all be computed at low costs.

Phase 3

The third run is the data recovery run and is only performed when more detailed answers of a particular superelement are requested. For this run the (upstream database) .DBALL dbset, is necessary, besides the .MASTER dbsets of the residual structure and the reduced component. The data recovery run contains:

- ASSIGN and DBLOCATE statements.
- A DMAP alter in order to perform only data recovery.
- SEDR (data recovery) command for specific superelement.

Typically, the output will be straightforward stresses and strains of the specific superelement.

2.3 Frequency domain analysis with TricaT

During the design process of commercial vehicles, we are often interested in the following aspects under various vehicle speed and road conditions:

1. ride comfort evaluation
2. fatigue input loading of components (load histograms)
3. springtravel and tyreforces
4. accelerations of components

With MSC/NASTRAN the dynamic response is calculated using SOL108 yielding displacements of all points of interest. For each wheel a subcase is defined prescribing a unit displacement of that particular wheel only using Lagrange multiplier method. The postprocessing of the thus calculated FRF'S of the residual structure is performed with the aid of TricaT. Figure 5 shows an overview of the TricaT analysis.

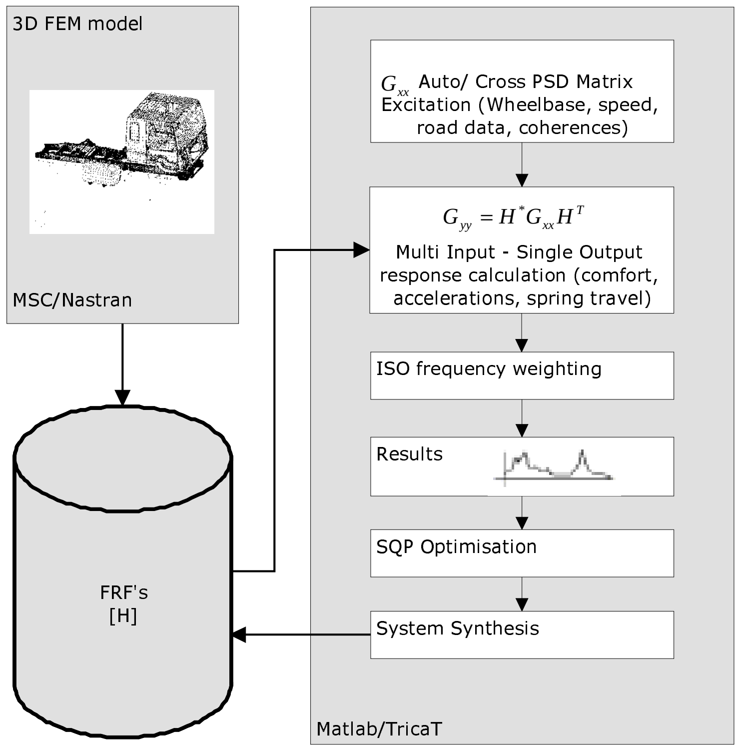

Figure 5 Frequency response analysis and post-processing with TricaT.

The Power Spectral Density (PSD) function of the response $G_{yy}(f)$ can be estimated with:

$$G_{yy}(f) = H^*(f) G_{xx}(f) H^T(f),$$

Where $H(f)$ is the matrix of FRF'S, and $G_{xx}(f)$ is the excitation matrix built in TricaT [3]. The $G_{xx}(f)$ matrix contains Auto Power Spectral densities on the diagonal, while the off-diagonal terms are filled with Cross Power Spectral densities. These Cross Spectral density functions are calculated with the coherence function between two tracks (left and right hand side wheel) for a certain road. Also the phase-lag between front and rear wheels is taken into account. In TricaT, the excitation matrix of several road types can be built: bricks, motorway, Belgian cobble stones etc. Also, the excitation matrix can be created for load cases such as idling and wheel-imbalance.

For ride comfort evaluations, the human sensitivity to vibrations is incorporated by applying frequency dependent filters according to ISO 2631 to the output.

System synthesis and optimisation

In order to investigate the effect of parameter changes a system synthesis module [4] has been built into TricaT. The system synthesis module is based on coupling FRF'S of linear systems

and enables fast design sensitivity of mass, stiffness and damping of scalar elements, without having to recompute the FEM model. Therefore, the residual structure run has excitations at the wheel and at either side of the scalar elements to be modified.
Similarly, design optimisation of mass, stiffness and damping can be performed using MATLAB'S optimization toolbox. In this case the optimization is translated to the minimisation of a predefined goal function containing any number of PSD's.

3. Examples

In practice two types of design studies are performed: geometric and parametric. Typical problems to be solved with geometric design studies are: Where should a cross-member be ideally located? Can the engine-gearbox assembly be moved without problems? On the other hand parametric design study may deal with problems as: What springrate should the optimal cabin, engine or axle suspension have? What is the ideal shock absorber for the cabin suspension?
The presented working method shows the ability of quickly assembling complete vehicle models. Consequently, most geometric design studies can easily be dealt with. The parametric design problems are tackled with the use of TricaT. Figure 6 shows a typical ride comfort PSD for different operating conditions. Figure 7 displays some results of a parametric study of the rear lateral cabin damper. Figure 8 features a typical design sensitivity result.

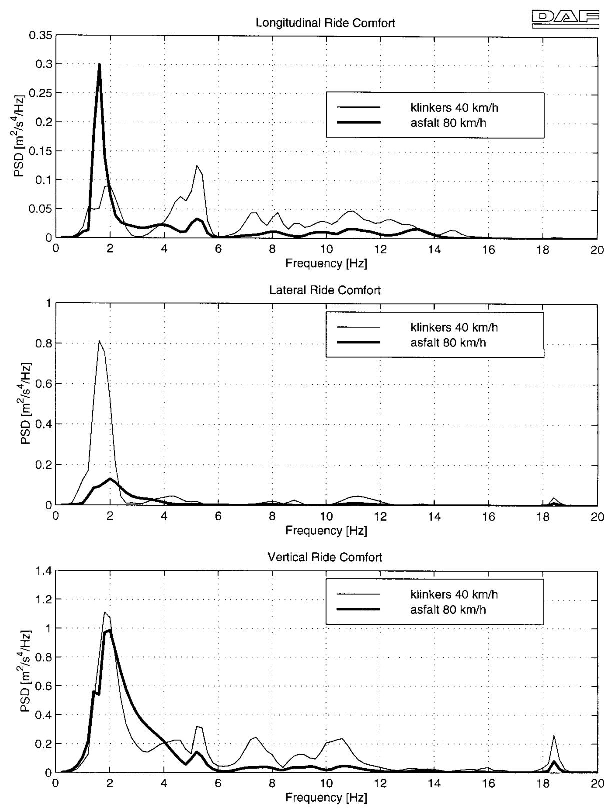

Figure 6 Ride comfort in three directions for bricks (40 km/h) vs. Motorway (80 km/h).

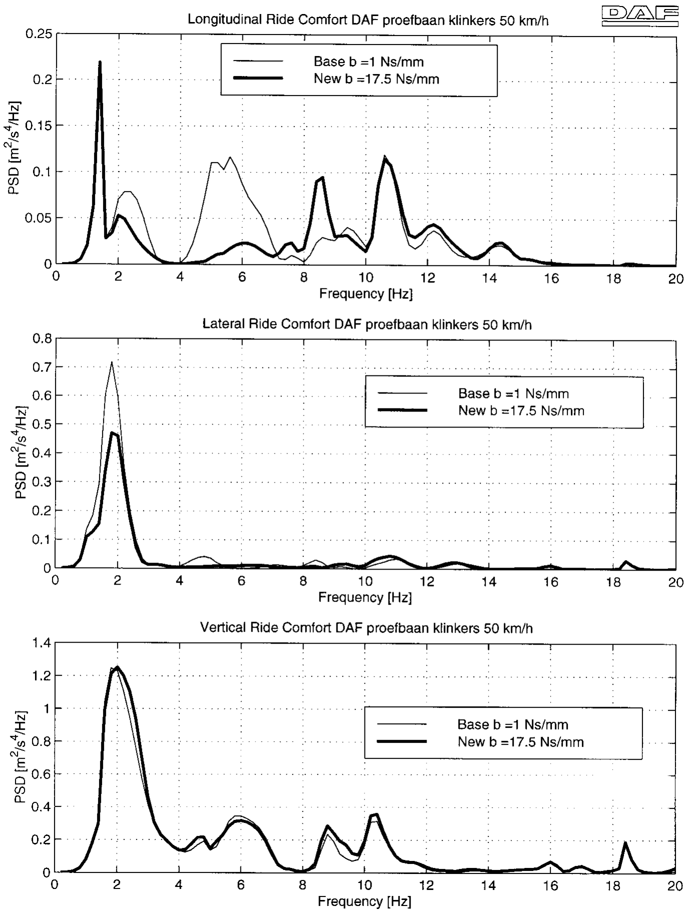

Figure 7 System synthesis of cabin damper.

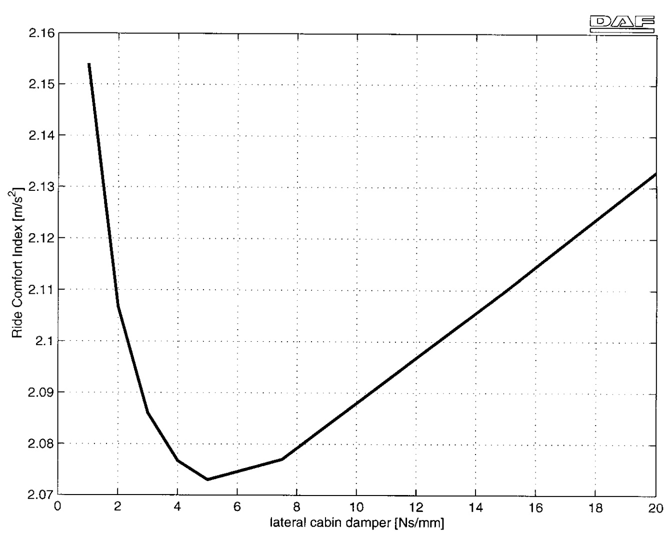

Figure 8 Design sensitivity results: ride comfort vs. cabin damper.

Summary

A substructuring approach, devoted to the creation and assembly of external superelements has been presented. The calculated database files are stored in a component library for repeated use. In addition the assembly of the complete vehicle models has largely been automated and therefore has become less time-consuming. On the other hand the postprocessing of the PSD functions for different operating conditions can be performed quickly without having to re-compute the residual structure. In the same way, also fast design sensitivity and optimisation studies are possible.

References

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