THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING
IN SOLID AND STRUCTURAL MECHANICS

A Methodology for Efficient Conceptual Design Analysis of Nonlinear Dynamic Structural Systems

NICLAS ANDERSSON

Department of Applied Mechanics
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden, 2013

A Methodology for Efficient Conceptual Design Analysis of Nonlinear Dynamic Structural Systems

NICLAS ANDERSSON

THESIS FOR LICENTIATE OF ENGINEERING no 2013:17
ISSN 1652-8565

Department of Applied Mechanics
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone +46 (0)31 772 1000

Chalmers Reproservice
Gothenburg, Sweden 2013

A Methodology for Efficient Conceptual Design Analysis of Nonlinear Dynamic Structural Systems
Niclas Andersson
Department of Applied Mechanics
Chalmers University of Technology

Abstract

There is a typical requirement conflict between fuel consumption and noise and vibrations in passenger cars. Obviously the combustion engine is a major source of vibration and has an influence on vehicle emissions. Similar properties apply to the power transferring mechanical driveline system. Many driveline design concepts that aim to reduce carbon-dioxide emissions intensify and add new vibration problems, since the majority of them affect vibration sources or system damping. In conceptual design of drivelines, many possible concepts proposals are studied in parallel. This situation calls for modelling and analysis that can meet the demand for rapid virtual prototyping. Conflicting to this is the trend in which models have become extremely detailed to meet demands from others than conceptual designers. The complex behaviour of the driveline system in combination with often highly specialised component models result in system models that at their best are valid only near a few specific stationary operating points. This makes is difficult to study the effectiveness of possible component design changes in early development phases. Instead, this is first revealed during system verification testing, when fundamental design changes since long are unrealisable. This work focus on models for conceptual design, *i.e.* models that are not over-parameterized. The aim is to find the balance when models are as simple as possible but as accurate as required by conceptual design studies. A methodology is proposed, based on knowledge of existing automotive methods and workflow, that with provided modelling tools has the potential to serve this purpose within the nearest future.

Keywords: Nonlinear dynamics, Flexible multibodies, State-space models, Model order reduction, Component Mode Synthesis, Balanced truncation, Conceptual design models and Driveline systems.

Preface

The project *Conceptual Design Models for Premium Driveline NVH Characteristics* was initiated by the author at Volvo Car Corporation, Department of Transmission Engineering, where it was started in 2008 under the wings of the *Volvo Industrial Ph.D. Programme*. This thesis is the result of work conducted by the author within this project during 2008-2013 at the Department of Applied Mechanics, Division of Dynamics, at Chalmers University of Technology. The funding comes from *Volvo Car Corporation* and *Energimyndigheten*.

The following persons are acknowledged for being a critical part of this work: *Thomas Abrahamsson* for always carrying a good mood around and regularly, with painfully accurate precision, pointing out the weak spots in my arguments to make me reconsider and learn. *Lennart Andersson* for supporting the development of the powertrain model and pushing the right buttons within Volvo Cars. *Raoul Rinaldo* for guiding my thoughts related to systems engineering. *Anders Boström* for accepting the project in the first place and since then patiently overlooking the progress. *Fredrik Warnström* and *Martin Olsson* for accepting my modelling initiative and constructively developing the powertrain model, always in an extremely helpful way. *Stephan Denzel* for help with physical testing and measurements included in Paper A. *Björn Pålsson* and *Mikael Bigert* for helping me out with design of experiments, also for Paper A. *Magnus Andreasson* for solving many issues related to NASTRAN and Paper B. *Fredrik Sjöström* for lending me his expertise in questions related to ADAMS solver.

And at last but certainly *not* least, actually what matters the most to me in life, my loving family: *Maria*, *Viktor* and *Vera*.

$$\left(\frac{5y}{4} - \sqrt{|x|}\right)^2 + x^2 = 1$$

Ytterby, August 2013
Niclas Andersson

Thesis

This thesis consists of an extended summary and the following appended papers:

Paper A N. Andersson, T. Abrahamsson, Driveline model calibration and validation in an automotive 4-cylinder Diesel application, *Proceedings of the International Noise and Vibration Conference, Leuven, Belgium, 2012 September 17-19*, Leuven (2012), pp. 3841-3855.

Paper B N. Andersson, T. Abrahamsson, Linear time-invariant component reductions in a large-scale automotive dynamical powertrain model. *To be submitted for international publication.*

The appended papers were prepared in collaboration with the co-author. The author of this thesis is responsible for the major progress of the work including planning, modelling, implementation, simulation, analysis and writing. The author planned and partly participated in the physical testing reported in Paper A.

Contents

Part I

Extended summary

1 Automotive background

The automotive industry is one of the world's most competitive businesses and demands on the final product, its cost, development time and environmental impact increase continuously. For example, a passenger car in the so called premium segment must deliver high performance engines, luxurious driving comfort and product design that follows the latest lifestyle trends. Among these values, improved vehicle performance has historically been the most typical premium customer demand and has been met by development and refinements of combustion engine technologies that are now well established. Larger and more powerful engines lead to higher loads and vibration levels in many attached mechanical subsystems, as well as to higher vehicle fuel consumption. This trend has been held back for the last decades mostly by Californian emission laws and standards. As a result, further refinements of existing combustion concepts followed together with advanced drive cycle balancing, where lower idle speed and optimised transmission control strategies in combination with reduced system damping helped to, on the average, meet the emission requirements. This tactic, however, increases the level of disturbing noise and vibrations and thereby reduces the in-vehicle comfort, which is another critical value for most existing and potential premium brand customers.

1.1 The driveline

The *powertrain* of a normal vehicle consists of an *engine* and a *driveline* system, see figure 1. The driveline transfers engine power to the tyres and the combined dynamical characteristic is critical for the car's fuel consumption, comfort and driving experience. The driveline is a strongly *nonlinear* mechanical system, including backlash, friction, rotating shafts, gears, drive shafts, etc, which contributes to making several complicated and non-intuitive dynamical responses possible within the system. Its dynamical response can result in multiple critical vehicle error states, known within the automotive industry as *gear rattle*, *clutch judder*, *propshaft whirl*, *driveline*

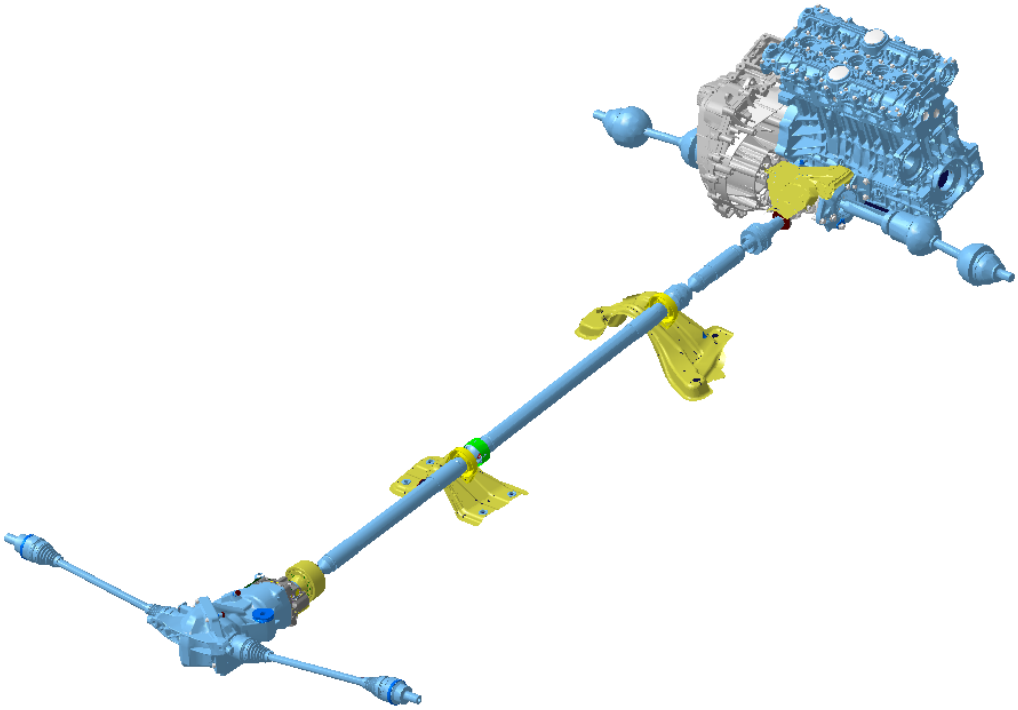

Figure 1: Virtual overview of an all-wheel-drive powertrain system.

clunk, low-frequency *booming*, etc. When problems appear, lack of understanding of the underlying nonlinear phenomena makes it difficult to investigate the effectiveness of possible design changes to remedy the occurring states of error.

1.2 Methods currently in use

With rather consistent societal conditions and customer requirements, the dominant product development approach within the automotive industry has since long been experience-based physical development testing in combination with advanced vehicle application tuning. A considerable amount of engineering man-years has been put into the calibration and optimisation leading to the powertrain-vehicle integrations of today. From this follows that it is not an easy task to successfully make quick re-calibrations in late development phases. When vibration problem appears during physical testing, *experimental modal analysis* is used to establish a mathematical model from measured data, normally from multi-input multi-output tests, see [1]. Such a model can be of great help in analysing occurring responses in order to make effective last-minute development changes. However, since this method is based on the theory of linear systems it cannot be expected to be valid for nonlinear phenomena occurring in the driveline system. Another drawback is that it requires at least hardware prototypes and consequently is of less help during early design stages. Other, so called, virtual product development methods exists and make it possible to simulate and analyse design solutions before the first hardware prototypes are produced. Both *finite element* models and interconnected *multibody system* models are since long used within the automotive industry, see figure 2 for a few examples and [2, 3] for theories. The general disadvantage of these virtual methods is the usually quite large modelling errors that are normal for more complex system descriptions. Similar to experimental methods, this results in that virtual methods today are best used for verifying analyses and not conceptual design studies.

1.3 Development challenges

In recent years, following a major world-wide debate about global warming and more specifically the recently sharpened European legislations for reduced *carbon-dioxide* emissions, [4], the since long established business concept of the premium segment have been replaced by one that, in practice, requires physical downsizing of also the top performance engines or a rapid transition to electro-mechanical hybrid vehicles. All of a sudden, companies that want to be competitive and profitable on the automotive market have to quickly find new power generating and distributing concept solutions that deliver the same customary premium vehicle qualities, but in addition are more environmental friendly than ever before. This have resulted in a genuine race for new green powertrain technologies that help to substantially lower the carbon-dioxide emissions.

Too meet these imminent requirements and expectations, development of new powertrain technologies are currently on-going, such as combustion engines with reduced number of cylinders, dual-clutch manual transmissions, kinetic energy recovery systems and combustion-electrical hybrid powertrains. To be able to faster put more environmental friendly solutions on the market, many other important but less comprising developments are also on their way. Examples of such are reduction of mass and mechanical losses in existing solutions, loading the engine down to idle speed while reducing engine idle

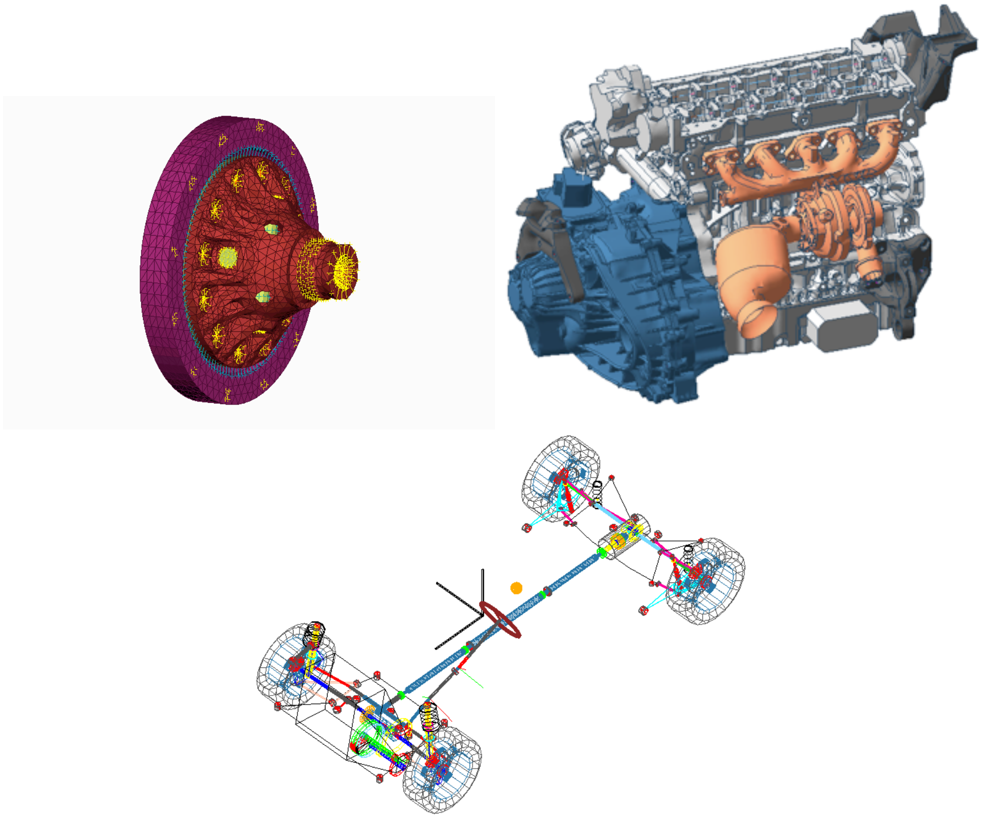

Figure 2: Examples of finite element and multibody dynamic subsystem models from automotive powertrain applications. Individual scaling is used.

speed even further, intermittent engine start-stop in city traffic and lock-up functionality of automatic gearboxes. Common to almost all of the mentioned solutions are that they are expected to intensify and add new comfort related problems by affecting the sources of vibration or system damping. Also, with added new technologies the already high system complexity will increase further.

Since the development of many components and subsystems are out-sourced to suppliers external to the original equipment manufacturer, both major and minor system related problems could appear for the first time during the verifying development phase. The success of implementations of new technologies in an already complex and sensitive system depends a lot on the ability to predict powertrain system nonlinear dynamical characteristics early-on in the design process, when it is still possible to choose a better combination of conceptual component solutions that does not compromise other premium values in order to reach the intended carbon-dioxide reduction. If this is not possible, there is a great risk that implementations of developed technology solutions are stopped before reaching the paying customer, or that multiple other vehicle qualities are compromised to solve the specific problem at hand. Unfortunately, there is currently a lack of both effective and valid conceptual methods and, consequently, the knowledge required to control the risks. There is not much room for major mistakes and the stakes are high, since not every automotive company is expected to survive the recent radical change of business.

2 Problem formulation

From the given background the linked main drivers (needs) of this research is concluded to be:

- Design solutions to occurring noise and vibration problems in today's vehicles
- Balanced implementations of upcoming more environmental friendly powertrain technologies
- Effective conceptual design models for prediction of fundamental system characteristics
- Generally valid models for simulation of complex nonlinear structural systems
- Better knowledge of nonlinear dynamical phenomena

In the conceptual design process of cars, many possible driveline concepts are studied in parallel. The trend is shorter product development cycles to meet market demands. This situation calls for modelling and analysis that can meet the demand for rapid prototyping. Conflicting to this is the trend in which models have become extremely detailed to meet demands from others than conceptual designers. Much effort is made to establish detailed finite element models good enough for stress and stiffness estimations in the sizing process. For handling, multibody dynamic models are set up including major inertia, flexibility and component connectivity in the car. These are most often heavily parameterized models that includes product and component data that are collected and updated many times over the development cycle. Here we focus on models and methods for conceptual design. Typical features of conceptual design is that there is often lack of information about details, there is a large variety of design options to choose from and the simulations made at this stage aim for "the big picture" with lesser demand for simulation precision. For the conceptual design of driveline components it is most essential to catch possible error states that results from its nonlinear behaviour and to study the robustness of the system against such error states. To allow for efficient conceptual design modelling and analysis the models involved must not be overparameterized. We need to find the balance for when the models are as simple as possible but as accurate as required by conceptual design studies. The models searched for are ultimately parameterized using physical insight.

The overall vibration properties of the car, and especially the noise and vibration environment as felt by the driver and passengers, is the aggregate properties of the system as a whole. No subsystem can be held as sole responsible for high vibration magnitudes within the complete system. In the car, the powertrain is seen as the source of vibration and the car compartment the receiver of vibration. The system properties are determined by the source-receiver matching.

The powertrain (including the driveline) interface to the rest of the car with connection elements such as bushings, springs and dampers. The powertrain is flexible under loading and so is the rest of the car. We here focus on the powertrain and its internal nonlinear connecting elements. We assume that for the vibrations caused by the powertrain itself, the rest of the car behaves more or less linear. Our main interest is limited to stationary operating conditions, which is motivated by our focus on conceptual system design.

The goal is to develop both understanding of underlying phenomena and to set up efficient models for the qualitative and quantitative analyses that are necessary to treat occurring dynamical phenomena related to nonlinear driveline components of passenger cars at the concept development stage. We want to integrate linear and nonlinear components into a model that describes the system's fundamental dynamical properties. The ultimate goal is to enable driven powertrain engineers to design for an avoidance of unacceptable dynamical responses and to prescribe required component properties in balance with conflicting system qualities, such as vibrations, carbon-dioxide emissions and drivability.

2.1 Research context

The key issue in conceptual design is the model complexity. It needs to be simple to allow for parameter studies and use as little product data as possible to keep up with the fast pace of the design cycles. The key phrases are thus minimum parameter models, that involves as few physically based parameters as possible and models of minimal order that has as few states as possible, which allows for rapid simulation. This makes it practical to do rapid parametric studies, robustness evaluations, optimization and others that require a lot of evaluations.

Further, in systems with multiple nonlinearities it is critical that these are described as (at least) phenomenologically nonlinear and that they may interact during simulation. This make way for nonlinear system interactions, which are likely to contribute to the sensitivity to parameter variations of a non-robust system.

Scientificly related issues are, in short:

- Model reduction in systems with multiple nonlinear components
- Model reductions considering balance between prediction accuracy and model order
- Nonliner dynamical interactions
- System identification in nonlinear systems

The initial research questions were:

- What are the minimum parameter models of nonlinear components that may be used to predict powertrain error-states that normally occur?
- How may these components be synthesised into a system model of minimum order that also includes components that behave linearly?

3 Proposed methodology

The guiding principle is to keep models as simple as possible but as complex as necessary for sufficiently accurate prediction ability. Our research approach is to go from an overparameterized system model consisting of connected and generally moving linear and nonlinear components that captures real occurring responses, down to a low order model that still captures the fundamental phenomenon and also have a chance of being qualitatively understood. To obtain a system model valid over the whole operating range it is important to model the kinematics of included joints and physical load paths of the relevant system configuration, as well as correct structural mass and stiffness distributions. From experience in automotive engineering, much of the non-robust responses seen in a complex system relate to how nonlinear joints couple the linear structures of the system. To prevent making intuitive model simplifications and risk loosing critical responses without knowing it, it is important to use objective reduction methods that can guarantee a specified prediction accuracy. To characterise a nonlinear system and evaluate design parameter variations, it is necessary to simulate responses and interactions of many different operating conditions. This requires effective models, possibly having multiple simultaneous nonlinearities, that allow interactions to form within the reduced system. To better align simulation results with a design process largely based on physical development testing, the virtual system synthesis is based around physical component interfaces. Apart from facilitating system requirement cascading down to subsystem specification, this allows necessary component modelling details to be locally resolved (or the opposite if such information is missing in early development phases) while the larger system can still be included in the simulation. Physically meaningful component design parameters should be used in order to study how these influence the system response and every chosen design solution be checked to work also in the full system model together with other subsystems.

In the automotive industry, a dedicated group of development engineers and others often work closely together to fulfil given time, technical and cost requirements. This is generic for development projects on different scales and system levels. They all have the common task to develop solutions that are to be presented to superior decision makers. Depending on the phase of development these deliverables can be in terms of presentation of several more or less vaguely proposed design solutions, specific design analysis and verification reports or developed hardware prototypes. Next we go through the main steps of the modelling, simulation, design and delivery parts of the proposed general methodology.

3.1 Modelling

In order to predict the dynamical behaviour of different combinations of component design solutions and rank them according to a given set of system requirements, it is recommended to have a model representation of the system. In early development phases, when no hardware prototypes are available, virtual methods are best used for this. Component models are then given known physical properties and their equations of motion are formulated and combined into a system description. We propose the following major modelling steps.

- **Linear structures**: (a) Use overparameterized structural models (feasibly finite element component models). (b) Define a small set of component external interface nodes, which well represent the macro geometry of the connection points of the corresponding physical structure. (c) Assemble larger structural blocks that are assumed to behave internally as linear structures by coupling matching component interface *degrees of freedom* (DOF).

- **General component reduction**: (a) Reduce the order of the linear block models using input-output based reduction methods to meet a specified prediction accuracy. Use methods that allow objective elimination of system states that do not significantly influence general input-output relations between loading and response of interface DOF.

- **Nonlinear components**: (a) Model nonlinearly behaving components using a set of algebraic or differential equations involving a minimal set of physically meaningful (and measurable) parameters. (b) Include interface node DOF in the formulation to similarly represent the macro geometry of the connection points of the modelled physical component.

- **Component connections**: (a) Specify how interface DOF of structural blocks and nonlinear parametric models should be coupled. A connection model is considered as much a building block as any other component model.

- **System synthesis**: (a) Assemble a nonlinear interconnected multibody system model of largely moving flexible bodies, by placing linearly reduced and nonlinear parametric models in a relevant system configuration. (b) Apply the interface DOF constraints of the connection models.

3.2 Simulation and intermediate results

To obtain a prediction of the resulting system response, the set of formulated equations of motion are solved by numerical time integration on digital computers. To account for many physical properties not included in the models, comparison with known or measured behaviours must be done. In this process and afterwards, simulated responses can be used directly to answer a single specific question, but often more valuable in conceptual and design analyses is to extract and understand the fundamental character of the system. To this end the following steps are proposed.

- **Model calibration**: (a) Simulate the system response corresponding to a real occurring problem. (b) Refine component models if necessary to capture the response of interest and calibrate the component model parameters until the system behaves (at least) qualitatively correct over the load-speed operating range. From a practical point of view, the intended purpose determines when the model can be considered valid.
- **Component boundary conditions**: (a) Obtain resulting load distributions and system deformations for multiple operating conditions from validated system simulations. This is critical for efficient design analyses of components in large complex systems, since over-conservative or even incorrect load and boundary conditions are often a dominating source of error.
- **System normal mode variation**: (a) Map how linearised system modes vary for different load cases, load levels, design parameter values and rotational speeds (frequencies). In combination with knowledge about dominant system excitations this suggests where system resonances are likely (not certain) to appear. (b) Use such information for predicting qualitative system characteristics for comparison of different conceptual design proposals, or suggest potentially critical operating conditions for design of virtual or physical tests, as well as diagnosis of new resonant behaviours appearing during verification.
- **Nonlinear system response**: (a) Perform system simulations of the full nonlinear time responses, possibly including primary and secondary resonances, energy exchange due to modal interactions, limit cycles and instabilities, etc, see [5].

3.3 Design loops

To compare and rank multiple design proposals with respect to dynamical characteristics, for ranges of design parameter values and operating conditions, in complex and strongly nonlinear systems and within the time frames of rapid product development processes, require apart from valid models also that many system response simulations be evaluated in a short period of time. These in combination with creative and interactive design engineers enable quickly evolving design iterations, which are found important for obtaining system solutions with a high degree of market readiness. To facilitate such a process, we propose the following steps.

- **Specific system reduction**: (a) Perform more specific reductions on the system model using objective methods. Use previously simulated time responses and a set of specific analysis questions, alternatively a directly appearing problem. This can be done by further component reductions or by establishing mathematical models after analysing system responses, see for example [6, 7].
- **Design parameter variations**: (a) Use specifically reduced system models to simulate responses due to a large number of design, load and speed parameter variations. (b) Use these results to predict or estimate system robustness and instability margins of a number of candidate system solutions. (c) Verify that the chosen design proposals work properly by updating and re-running the previous, more generally reduced, system model. (d) For models of only a few DOF, seek analytical or semi-analytical solutions to reveal combinations of parameter values that control resonant behaviour, see [5].

3.4 Deliverables

Results from previous simulation steps now help to build a powerful proper understanding of the system characteristics. Such knowledge should be used to carefully formulate analysis questions that can lead the further design process in a good way. These are probably qualitative questions that will fail to answer the most specific concerns, but instead and better off, make it possible to verify the development progress much prior to late hardware system verification tests.

- **Local stress and strain**: (a) Obtain local stress and strain for component dimensioning, fatigue life prediction and requirement specification from detailed quasi-static contact analyses, etc, by using previously calculated interface loads and boundary conditions. (b) Use these results in component design and verification in a step which often is performed separately and parallel to other developments.
- **Existence & margins to resonances**: (a) Obtain knowledge about which resonances to expect within the simulated system and in what

regions of the operating space. (b) Do design parameter variations to provide a qualitative idea of how far away critical responses are from the nominal values, or vice versa, if the problem can be solved by modifying a specific component parameter within a physically reasonable range.

4 Summary of appended papers

4.1 Paper A

In Paper A, *Driveline model calibration and validation in an automotive 4-cylinder Diesel application*, we calibrate and validate a newly specified and implemented flexible interconnected multibody system model. For this, we run a prototype of a front-wheel-drive powertrain in a physical rig test and a nonlinear driveline torsional resonance response is identified. A minor parameter study using the computational model shows how parameter settings of selected components influence the system normal modes. The measured responses are then replicated by steady-state simulations.

4.2 Paper B

In Paper B, *Linear time-invariant component reductions in a large-scale automotive dynamical powertrain model*, we describe an implementation of two additional component reduction methods into the normal workflow of computational softwares Nastran and Adams. Four reduction methods are applied to selected components of the powertrain model used in *Paper A*. Two of these methods consider specific input-output relations that can be utilised to balance the prediction accuracy and computational effort. System simulations are run over the engine speed operating range and responses related to vehicle noise and vibrations are evaluated for each reduction variant. The prediction accuracy, reduction and response simulation times for different model orders are considered in the study.

5 Concluding remarks and future work

This work aims at developing modelling tools that will lead to a better use of virtual simulations in the automotive design process. We have focused on two major paths to achieve this. First, improving the predictive capabilities of existing simulation models by using correct structural distributions and a greater number of nonlinear connection components. Secondly, using objective methods for balancing component model order and the corresponding prediction accuracy, to allow the advanced system simulation models to be reduced and effectively used in early system design phases.

In *Paper A*, which was the *finale* of the first episode of a related model-development project, we present a computational approach to driveline simulations that captures a nonlinear system torsional resonance and its changes with increasing load and engine speed. The system model is not limited to that specific response mode and is capable of capturing other nonlinear system responses after calibration. In *Paper B*, two state-space reduction methods that consider defined input-output relations are evaluated and implemented into the normal virtual development workflow. Both of these methods are shown to have an equivalent accuracy to standard methods used by commercial multibody dynamics software and to be more general and time effective. We conclude that the developed modelling tools add functionalities and are better apt for effective structural simulations in early driveline design phases than the standard methods used today in the automotive industry.

There are of course still much to do before fully reaching our goal, but we think we have started off in a good direction for future efforts. Most important now is perhaps to use the powertrain model in simulations for different applications, configurations and operating conditions. Much calibration and model refinement work still remain until the full benefit is reached. There is an industrial need to map and study nonlinear system responses occurring across the parameter space, in order to learn more about the powertrain system character and how to design more robust drivelines. To further develop the methods, one suggestion is to study and apply methods for identification of minimal sets of component design parameters that are required to capture occurring system responses. With such information available, qualitative methods for time series analysis can be used to establish the most effective reduced order system design models.

Looking even further ahead, both transient responses and powertrain-vehicle interactions could be very meaningful to look into.

References

[1] D. J. Ewins *Modal Testing: Theory, Practice and Application*, Second Edition, Research Studies Press, Baldock, Hertfordshire, England (2000).

[2] R. D. Cook, D. S. Malkus and M. E. Plesha, *Concepts and Applications of Finite Element Analysis*, Third Edition, Wiley, New York (1989).

[3] A. A. Shabana, *Dynamics of Multibody Systems*, 3$^{\text{rd}}$ edition, Cambridge University Press, New York (2005).

[4] European Comision (2013, August 26). Retrieved from http://ec.europa.eu

[5] A. H. Nayfeh and D. T. Mook, *Nonlinear Oscillations*, Wiley-VCH, Berlin (1995).

[6] L. Ljung, *System Identification: Theory for the User*, Second Edition, Prentice Hall, New Jersey (1999).

[7] H. Kantz and T. Schreiber, *Nonlinear Time Series Analysis*, Second Edition, Cambridge University Press, Cambridge (2004).