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IN SOLID AND STRUCTURAL MECHANICS

Characterisation of Nonlinear Structural Dynamic Systems in Conceptual Design

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Abstract

The engine and driveline systems of passenger cars generates and distributes the necessary driving power and are major contributors to vehicle emissions, noise and vibrations, etc. More environmental friendly technologies under development are expected to intensify and add new comfort related problems, since most of them affect vibration sources or system damping. A successful balancing of fundamental system qualities requires a better use of simulation in early design phase. This work focus on virtual tools for analysis of low-frequency structural dynamic vibrations. In conceptual driveline design, many possible system solutions are studied in parallel and their often nonlinear behaviour requires robustness evaluation across full operating and design parameter ranges. This situation calls for virtual methods that are generally valid and meet the demand for rapid prototyping. Thus, models need to be as simple as possible and as accurate as required for capturing phenomena that occur in real drivelines. Further, analysis tools must efficiently process data sets from extensive parameter variations and extract fundamental system characteristics that can be used to reliably rate competing proposals. For this, a complementing design analysis methodology is proposed that improves current automotive development tools and workflow. A general and over-parameterised multi-body system model is constructed from detailed linear structural and schematic nonlinear parts. State-space reduction methods are then applied to modal components to balance prediction accuracy and evaluation speed of resulting conceptual design models. Parameter variations in fully known system models are simulated under ideal periodic loading and low noise conditions. A feature based frequency analysis approach is used to extract precise system characteristics and sort responses into qualitative classes. To efficiently process large amounts of generated data, statistical learning methods are used to automate the response classification.

KEYWORDS: Multi-body dynamics, Structural dynamics, Model order reduction, Frequency response functions, Nonlinear characterisation, Stepped-sine, Multisines, Response classification, Support vector machine, Concept design analysis, Driveline systems.

Preface

The research project *Conceptual Design Models for Premium Driveline NVH Characteristics* was initiated by the author and started in 2008 under the wings of the Volvo Industrial Ph.D. Programme. This thesis is the result of work performed by the author, first during the years 2008 and 2011-2013, at the Department of Applied Mechanics, Division of Dynamics, at *Chalmers University of Technology*. Then, between 2015-2018, at the Department of Transmission Engineering, at *Volvo Car Corporation*. The project has been paused several times with no or little progress, due to financial crisis and other work in prioritised development projects, etc. *Volvo Car Corporation* and *Energimyndigheten* have funded the work.

The following persons are acknowledged for also being a critical part of this work: *Thomas Abrahamsson* for always carrying a good mood around and, with painful precision, pointing out weak parts of my argumentation. *Raoul Rinaldo* for inspiring discussions about conceptual design, systems engineering and machine learning, as well as, helpful suggestions for Paper C. *Lennart Andersson* for pushing the right buttons within Volvo Cars. *Anders Boström* for accepting the project in the first place and since then patiently overlooking the progress. *Stephan Denzel* for help with physical tests and measurements for Paper A. *Fredrik Warnström* and *Martin Olsson* for accepting my initiative and greatly contributing to the powertrain model used in Paper A and B, always in an extremely helpful way. *Albin Johnsson* for help with Python scripting for Paper C. *Mladen Gibanica* for help and discussions about multisines for Paper D. *Magnus Andreasson* and *Fredrik Sjögren* for solving many issues related to Nastran and Adams solvers, respectively. *David Andersson*, *Andreas Hall* and *Lars Wikander* for much assistance with applications and computer environment. *Lars-Olof Carlsson* and *Jörgen Stefors* for support and necessary push.

At last, most important in my life, my beloved family *Maria*, *Viktor* and *Vera*; and caring parents *Christina* and *Sten*. Thank you for your support and patience.

Ytterby, May 2018

Niclas Andersson

Thesis

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

Paper A N. Andersson and 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 and T. Abrahamsson, Efficient Component Reductions in a Large-Scale Flexible Multibody Model. Published in *SAE Int. J. Veh. Dyn., Stab., and NVH* 2(1):2018, doi:10.4271/10-02-01-0001.

Paper C N. Andersson, R. Rinaldo and T. Abrahamsson, Feature-Based Response Classification in Nonlinear Structural Design Simulations. Published in *SAE Int. J. Veh. Dyn., Stab., and NVH* 2(3):2018, doi:10.4271/10-02-03-0012.

Paper D N. Andersson and T. Abrahamsson, Comparison of Stimuli for Nonlinear System Response Classification, *To be submitted for international publication.*

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

Contents

Part I

Extended summary

1 Automotive background

1.1 Introduction and motivation

The automotive industry is arguably one of the world's most competitive businesses and the demands on the final product, its development cost, time and environmental impact increase continuously. For example, a passenger car in the so-called premium segment must deliver high performance, luxurious driver comfort and product design that follows the latest lifestyle trends. Among such values, improved vehicle performance is, historically, the most typical premium customer demand and has been met by development and refinement of combustion engine technologies that are now well established. Larger and more powerful engines lead to higher vibration levels in many attached mechanical subsystems and, thereby, more disturbing noise and vibrations in the car. Such annoyance is often mitigated by purposely added system damping to maintain high driver and passenger comfort, which is another critical value for many existing and potential premium brand customers. During the last few decades, this performance prioritised development has been held back mostly by American emission laws and standards (specifically the stricter Californian regulations), which limit the allowable emission of carbon monoxide (CO), oxides of nitrogen (NO_x), etc., as measured during well-defined synthetic driving cycles, [1]. The fact that these certifying tests differ from how the vehicle is typically used in traffic has allowed a continued development of high performance combustion concepts in combination with drive cycle balancing, where lower idle speed, optimised transmission control strategies and generally reduced system damping help to meet the specified average fleet emission requirements. Altogether, this has resulted in that modern vehicles deliver increasing engine power with a largely maintained fuel consumption. In recent years, following a major world-wide debate about global warming and city air pollution, general public opinion and state regulations have started to turn stronger against combustion engine technologies. Specifically, a revision of the European emission test method has begun, to better capture real driving circumstances with random testing of vehicles on the roads and fines for manufacturers who breach the rules, [2]. Circumstances like these have caused a fast replacement of the since long established business concept of the premium car segment, by one where substantially lower emissions are mandatory. Thus, companies that today want to be competitive and profitable on the high-end 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, so-called, green powertrain technologies that help to substantially lower emissions in traffic.

Consequently, development of powertrain applications with much new technology contents are currently on-going, such as turbo-charged combustion engines with reduced number of cylinders, kinetic energy recovery systems, electric-combustion hybrid and pure battery electric powertrains, which will increase the already high product complexity. Many recurring vehicle noise and vibrational problems today show nonlinear behaviour and are found to strongly relate to driveline responses. The same applies to occurring quasi-static or transient dynamic system responses that are critical for vehicle durability. Common to almost all mentioned design developments are that they are expected to intensify or add new comfort related problems by affecting the sources of vibration or system damping. When such problems appear, lack of understanding of the system dynamics and underlying nonlinear phenomena makes it hard to propose overall effective design changes to remedy the occurring state of error. Often unverified component design modifications are introduced in late development phases, which risk to compromise other vehicle qualities or increase mass production cost by requiring expensive alternative design solutions. To better address these issues by design require that fundamental driveline characteristics can be correctly predicted and analysed in early development phases. With such knowledge, well-suited physical dimensions can be specified that provide an overall robust and competitive technical platform, which then can be optimised for individual vehicle application projects having shorter development cycles. Since hardware prototypes are not available for physical testing until after later component design freeze, such design analyses must be done largely using virtual system modelling and response simulations. To be of good practical use in conceptual design analysis these models need to be valid and capture fundamental system characteristics across the full operating range, preferably using a small set of model parameters to allow for efficient evaluation of multiple design variants and parameter variations. Existing virtual tools within current driveline development instead focus much on material stresses in geometrically detailed component models and structural vibrations in over-simplified system descriptions, operating at a few discrete operating conditions. Hence, virtual methods are mostly used under the prevalent hardware-based component design and verification paradigm. Further, existing uncertainties about near and long term customer, legislation and infrastructural conditions drives the development of many optional powertrain variants and the number of subsystem combinations that need to be verified with respect to function and performance grows fast. The fact that the development of many driveline subsystems are out-sourced in parallel, to suppliers external to the automotive original equipment manufacturer, complicates the final vehicle verification process even more. Hoping to make best use of invested resources, only a selected few vehicle hardware prototypes are built for development testing. Although this selection is based on long term experience and careful considerations, there is a major risk that the most critical variant is not found before reaching the paying customer.

Thus there is a need for increased system dynamic analysis and synthesis to make sure that developed technologies can be successfully implemented into existing design solutions, under short development cycle constraints and increasing legislation and customer demands. To add value to the current industrial process such work should be started in the earliest development phases, which requires improved virtual system modelling and evaluation tools, as well as careful consideration of how to combine these into a conceptual design analysis methodology that effectively fits well into the industrial development process. Without such improvements, there is a great risk that newly developed technology solutions are stopped before reaching the start of mass production, i.e. if found compromising other crucial vehicle qualities or introducing new critical system failure modes.

1.2 Powertrain systems

The *powertrain* of a conventional passenger car consists of an *internal combustion engine* and a *driveline* system, see Fig. 1. The combustion engine is driven by internal explosions and converts translational piston motions to crankshaft rotation, and it is a fundamental source of vibrations in the vehicle [3]. For instance, the resulting driving motion of the flexible and

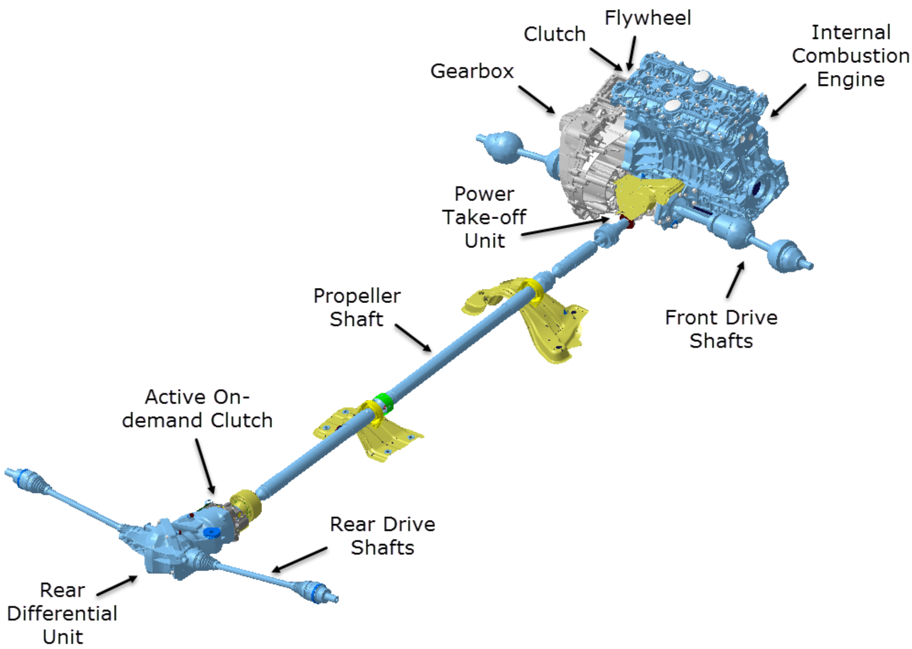

Figure 1: Overview of a conventional all-wheel-drive powertrain system of a passenger car, with its internal combustion engine and driveline parts.

unsymmetric crankshaft consists of multiple harmonic components of significant amplitude, also during steady-state operation. During operation onboard computers use measured values of throttle position, rotational speeds, etc., to control the optimal amount of fuel injection and timing of the complex system. The driveline primarily transfers and distributes engine power to the driving wheels, but must also withstand driving and road generated loads in the opposite direction. Its design has shown to be of critical importance for vehicle comfort, fuel consumption, driveability and durability. Most drivelines consist of multiple connected subsystems, such as flywheel and clutch, gearbox with differential unit and multi-link driveshafts. Many of these subsystems are themselves complicated constructions involving flexible rotors, gears and bearings, large deformation springs and drive joints that need precise design optimisation to function reliably and well under various possibly occurring system interactions. This requires that internally and externally generated quasi-static, as well as, harmonic and transient dynamic driveline loads and their resulting distribution throughout the system are known (or estimated). Every load transferring mechanical coupling is a potential strongly nonlinear element, with for example uni-directional contact and friction forces, which makes multiple complex and non-intuitive dynamical behaviours possible within the system. The large variety of responses and their often high sensitivity to small changes in parameters or initial conditions make such systems notoriously difficult to predict accurately. Powertrains with electric machines only, or in hybrid combination with a combustion engine, also exist and are currently under further development. These typically share front and rear driveshafts (and related occurring problems) with the corresponding conventional system but the remaining driveline parts can be quite different, both in mechanical design and dynamic characteristics. As an obvious example, electrified all-wheel-drive applications often use two separately located engines (front and rear) and the intermediate propeller shaft is not needed. Electric motors used have a larger operating speed range than combustion engines and are typically paired with a compact single-step planetary gear transmission (instead of multi-step or even continuously variable speed gearboxes) to cover the same vehicle speed range. Their major source of structural vibration stems from a resulting radial harmonic force, although significant drive torque ripples also exist. The motor speed is controlled by an inverter that use pulse width modulation technique, which results in noisy side-bands occurring symmetrically around a high carrier frequency [4]. Thus, many vehicle noise and vibration problems are expected to be of high frequency character, related to the rotor's operational speed. Still, the more fundamental low-frequency harmonic and transient dynamic system responses must not be overlooked in order to successfully develop robust, durable and comfortable driveline systems that are required by customers.

1.3 Driveline vibrations

A few occurring vehicle noise and vibration error states that typically result in complaints from paying customers are introduced next. The selected error types are often found related to the fundamental dynamical behaviour of the driveline. The errors are of special interest here as they are considered meaningful to address during conceptual design phases, by virtual system modelling and simulation of fundamental responses.

Gear rattle. The physical experience may be described as an audible broad-banded rattling noise during engine idle with manual transmission and engaged mechanical clutch, or with automatic gearbox and gear selector in neutral position. A similar noise can also often be heard during engine accelerating or decelerating driving conditions, typically in the engine's low-middle speed range. A common phenomenological understanding is that crankshaft rotational speed irregularities, due to inertial and combustion firing pulses, directly or by exciting a torsional resonance of the attached driveline system, feeds energy into unloaded meshing gear pairs (with rotational backlash) of the transmission, which responds with single and/or double sided tooth-flank contact vibrations. Alternatively, the same inertial and firing pulses result in powertrain mount reactions, as well as engine block and gearbox housing structural vibrations that feed energy into the unloaded gear pairs, which similarly responds with vibrational impacts. In cases of driveline torsional resonances with severe angular amplitudes, typically in applications with propeller shaft and hypoid gears, an alternating torque over a gear pair may result in repeated teeth contact openings and closures. The rattling response is strongly nonlinear and can show a high sensitivity to small changes in component data, initial conditions or load history and is difficult to specifically predict by simulations on any model level of detail. What can be done in early development phases is instead to predict the occurrence of fundamental torsional resonances in the nonlinear driveline system, how they vary with load and speed and possibly interact with other fundamental system resonance modes. Then, by system analysis and design specification of critical components, such as dynamically isolating dual-mass flywheels or advanced torsional vibrational absorbers, driveline resonance frequencies can be separated from major excitation sources at problematic operating speeds and thereby their vibration levels be kept below critical requirement levels.

Booming. Terms like *high-speed* or *low-speed* are sometimes used to differentiate between multiple booming variants relating to specific driveline applications. Low-speed booming is also known as *engine lugging* or *engine shudder*. The common physical in-vehicle experience is an audible disturbance during high torque acceleration, especially at gears of numerically low input-output speed ratio and in the engine speed range of 800-2000rpm. Alternatively with all-wheel-drive applications, an audible disturbance that typically occur during acceleration in the engine speed range of 2500-4500rpm. These responses are understood as general vehicle body (or chassis) structural resonant responses, excited by large amplitude crankshaft rotational inertia and combustion firing pulses, that are transmitted through the driveline system (mainly in engine speed range 800-1500rpm), as well as, through powertrain mount structural load paths (typically dominant above 1500rpm). Specifically in all-wheel-drive drivelines, propeller shaft bending vibration modes (in the frequency range of 100-200 Hz) are critically excited by rotational-lateral vibrations, induced by articulated drive joint kinematics, or rotating mass imbalances. Booming related driveline responses may be predicted from conceptual design phase, by simulation and analysis of the nonlinear system's fundamental torsional resonances and their variation with operational loads and speeds. By avoiding that major excitation orders coincides with fundamental system resonance frequencies of the operating driveline (typically most critical in frequency range 30-85Hz), the risk of transferring large amplitude vibrations from the driveline to the body structure can be reduced significantly. This can be obtained by careful specification of engine vibration isolating and absorbing components, as well as sizing of rotating component's dimensions, based on simulated responses under extensive design parameter variations. In propeller shaft applications, driveline torsional and bending system modes should be simulated across speed and load operating ranges and separated, by design, from the expected dominant order-based excitation of the rotating system.

Clutch judder. Periodic disturbances during high torque accelerations from low speed in drivelines with load transferring friction clutch. The response is phenomenologically understood as friction induced and self-excited rotational oscillations in the driveline system. The clutch friction torque varies over time due to multiple reasons, such as rotating shaft misalignments, clutch plate thermal deformations, changing lubrication properties, varying clutch slip-speed, clutch actuator normal force pulsations, etc., which may lead to periodic stick-slip oscillations or even dynamical instabilities. Since the physical problem strongly depends on the fine details of contacting solid and fluid parts, as well as the dynamics of the rotor bearing system, specific problem responses are most likely difficult to predict with less detailed models and without empirical data from specific physical tests. However, a conceptual rotor-bearing system model with contacts between solid geometries can be used to simulate known critical operating conditions and analyse the fundamental system dynamics under bearing and structural design parameter variations. Response statistics from such virtual experiments can then be used to indicate which parameter combinations that best avoid coinciding resonance modes, which is an qualitative criterion of a robust system that is less susceptible to stick-slip responses.

Take-off shudder. Audible disturbance or low frequency vibration sensed in the seat during full acceleration from stop or low speed. Vertical vehicle motions occurring during accelerations, in combination with significant driveline wind-up and shaft articulation at high torque output, results in significant drive joint kinematic and friction pulsating forces that excite fundamental elastic deformation modes of the engine and gearbox structures (5-15Hz) or propeller shaft and rear drive unit (15-25Hz). In-depth knowledge of the kinematics and qualitative behaviour of included drive joints, can be used together with the corresponding conceptual multi-body driveline model to predict related elastic mode resonances, as well as resulting critical driveline configurations and forced responses. Simulated responses with variations of parametric component inertias, rubber mount stiffness characteristics, joint types and operational characteristics can then guide the designer towards a robust and most achievable system solution.

First-order vibrations. In-vehicle experience that can be described as annoying vibrations sensed in the seat or steering wheel. The phenomenon is understood as occurring vehicle body or chassis structural resonances that are excited by the attached vibrating (and possibly resonant) driveline system, due to its rotating parts with mass imbalance, moving contact point, shaft off-set or misalignment, etc. With many potential excitation sources and long load transfer paths it is not likely that specific details of individual future problem responses can be accurately predicted with conceptual simulation models, but by studying the resulting system sensitivity to distributed first rotational order disturbances, it is possible to find more generally robust design solutions. Further, simulated operational driveline mount reaction forces can be characterised in early development phases and efficient counter measures be taken in later driveline installation or body and chassis design processes.

Other durability, driveability, vibrational and functional error states are heard of and known to relate to the driveline system design, in terms of unfavourable internal load distributions, flywheel whirl, shaft instability, vehicle shuffle, torque steer, clunk, etc. The corresponding problem descriptions are left outside of this text for brevity.

1.4 Conceptual development

A successful implementation of new technologies in an already complex system depends a lot on the ability to evaluate several significantly different alternative design solutions in early design phases, i.e. at a time when it is still possible to make significant changes without significant cost. However, during such conceptual phases much of the ultimately required design

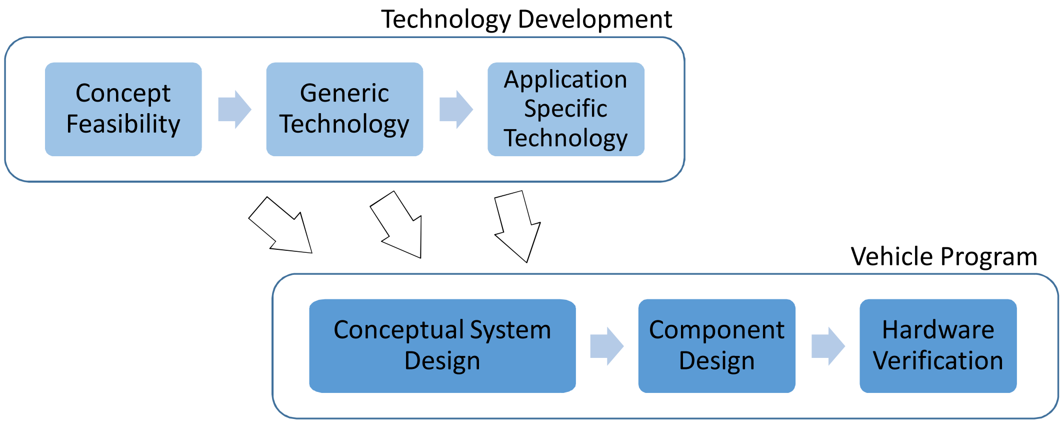

Figure 2: Principal overview of automotive mechanical development process.

information about surrounding parts and their behaviours are not yet available and predictions must often be based on previous component solutions or subjective best guesses. The automotive powertrain development process typically consist of multiple parallel vehicle programs, which each is mainly based on component design and hardware verification. Computer aided analyses are primarily used to accomplish faster component design iterations and analyse occurring problems that happen during later development phases. New technology needs to have a certain maturity to be considered for implementation in a vehicle program and are developed prior to the program start, as can be understood from the example in Fig. 2. Base technology often have longer development (and life) cycles compared to the vehicle programs and are therefore run in a separate preceding development process, where the specific complexity determines its start and duration. Each technology development process is then individually aligned with a specific vehicle program to smoothly output generic and more application specific technologies and transfer them to the product development process. Within each process, a given set of system requirements are adopted and successively cascaded to lower system levels. This results in specific subsystem requirements, with corresponding loads and boundary conditions, needed in order to design and verify subsystems in parallel work streams. The resulting design solutions are then assembled into a vehicle prototype (a so-called system mule) that is used in system requirement analysis and verification. After passing of an internal process gateway, the cascaded subsystem requirements may be rebalanced and another design loop initiated, based on the current system requirement fulfilment. Performing multiple design iterations on multiple system levels increase the overall product maturity and system robustness, which are likely to increase vehicle quality and customer satisfaction.

2 Problem formulation

Clearly, there exist many challenging problems within the automotive industry that call for a more system-oriented design approach, like successfully implementing more environmental-friendly technologies into existing driveline solutions, or developing new electrified powertrains. The main drivers of this research work have been a need for

- robust design solutions to recurring driveline noise and vibration problems in today's vehicles, and
- robust implementation of new driveline technologies in future vehicles.

Arguably, these difficult tasks are not solved without significant improvements of the traditional (evolved) component-based development process. The current situation can be much helped by better utilising virtual system design analysis tools in early development phases, which in turn drives the following necessary and more specific needs.

- Valid driveline models for interpretation and prediction of multiple nonlinear system resonance phenomena.
- Rapid evaluation of multiple conceptual system design proposals and model parameter variations.
- A complementary conceptual system design analysis process that utilises unique advantages of virtual simulations.

This requires improvement of current virtual modelling and analysis tools to better capture and predict specific system responses that are most likely to occur in real driveline and vehicle applications.

2.1 Design analysis challenges

In the design process of passenger cars, many possible driveline concepts are studied in parallel. The trend is shorter product development cycles to meet market demands. Typical features of conceptual design is that there is often a lack of information about component details, but a large variety of feasible system design options to choose from. Simulations made at this stage aim for "the big picture", with less demand for precision. This situation calls for simplified modelling and analysis to 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. Typically, solid component geometry descriptions are used to establish high resolution finite element models, good enough for estimating local material stress in the component sizing process. For driveability and handling, multi-body dynamic models are set up as aggregated inertial rigid parts with discrete flexible and ideal kinematic constraint connections. These are most often heavily parametrised models that are updated many times over the development cycle. Powertrain dynamic simulation models are often based on such overparameterised component models and are used to analyse critical responses that occur in physical tests, as well as to investigate the influence of component design modifications on the system behaviour. The use of detailed models are well motivated in verifying studies, since many customer complaints relate to structural vibrations that depend on detailed geometrical features, but not in early design iterations where the assembled model inevitably becomes impractical for rapid iterations and parameter variation. Intuitive based component simplifications are then often used to reduce model order and simulation time, and specific system linearisations are used for single-point response mode calibration. For nonlinear dynamical systems such models tend to have a limited validity in more general situations. For instance they do not capture well how fundamental response modes vary and interact with speed and load over the complete operating range and is thus of little help for analysing nonlinear phenomena.

In hardware prototype development tests in rig or vehicle, driveline related vibrational problems sometimes appear and disappear with minor changes in design or operational conditions, which indicates that the system is sensitive to small disturbances. Such behaviours can, in comparative tests with only a single modified part, be found related to a specific nonlinear component and further suggest that nonlinear dynamical phenomena occur in real life. To capture similar behaviours in simulations require that relevant nonlinearities are modelled, typically located at load transferring joints. This will, however, introduce an uncountable number of possible responses into the system, which makes it difficult to correctly predict which specific ones that occur in the real system.To evaluate sensitivity in nonlinear dynamical systems requires that many cases are run under distributed model and operating parameter variations. Statistical evidence can then provide a better understanding of the system's fundamental character and estimation of its robustness. However, there is no guarantee that the worst case will be found, even with arbitrarily large set of experiments. If simulations with extensive parameter variations have been performed, the result evaluation typically becomes a major bottleneck in the following process. Many proposed simple methods show good analysis qualities when applied to typical cases in small scale models, but are often less useful when applied to more general responses in large-scale systems, like complete powertrains, etc. Without a carefully selected analysis strategy and dedicated tools for efficient evaluation of large data sets, little of the available information data will be extracted and put to good use in the development process.

2.2 Methods currently in use

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 generally not easy to make successful re-calibrations in late development phases and it will most likely not become easier with upcoming introductions of new technologies and tougher requirements. Hardware tests are carried out in vehicles on track or on chassis dynamometer, where accelerometer sensors are attached to structural parts to measure their vibrations during specified operations. Such operational response tests are frequently used to identify the character of noise and vibrational problems that occur in specific driving situations with vehicle prototypes. Other stimuli-response tests are done with more controlled (and measured) excitations, to better analyse and extract structure displacement modes and frequencies of sub-assemblies or parts. Excitation signals commonly used are of random, swept harmonic, stationary harmonic and impact transient types, each with their different advantages and disadvantages [5]. Extracted *frequency response functions*

(FRFs) can then be used to identify main noise transfer paths. The methods used for *experimental modal analysis* [6] and *system identification* [7] are based on well developed linear theories, where measured time signals from multi-input multi-output tests are optimally fitted (in a least-square sense) onto an assumed state-space model structure of appropriate order. Still, successful analysis results are dependent on the skills of the test engineer in combination with practicalities, such as test object status, time for preparations, environmental and measurement noise, etc. This approach is generally of great help when analysing occurring system responses, for noise and vibration evaluation or effective last-minute powertrain installation modifications, but with the strong craving for hardware prototypes and since the nonlinear main vibration sources (like the powertrain rotor system) are typically not thoroughly analysed, it becomes less useful in early design phases.

Other, so-called virtual modelling methods exists and make it possible to simulate and analyse component and system design proposals before the first hardware prototypes are produced. *Finite element* [8] and *multi-body dynamic* [9] models are two such examples that are since long used within the automotive industry, see Fig. 3 for a few model examples. Early adoption and thereafter wide-spread use of computer aided engineering tools for component geometric design have lead to that the finite element method is the automotive standard approach to structural analysis. Typically, a detailed component geometry model is discretised into a solid finite element model with assigned mass and stiffness properties. Such geometrically detailed models (100-1000 thousands of nodes each) are usually used to calculate displacements, strains, and material stress under the assumption of small deformations and linear elastic material, but if necessary also under more general conditions. The same models are then used to build system models, by connecting intermediate components at their interface points. This results in large assemblies with many millions of degrees-of-freedom (DOF) that each is used to calculate the corresponding linear eigenmodes and frequencies. Such displacement modes are often interpreted as if they were physical properties of the system and weak sections of the structure (volumes with large modal strains) are taken as locations where to best add stiffening material to avoid structural resonances under normal operation. To evaluate system behaviours, with these large models and limited computer resources, frequency response calculations (typically in the range of 200-2000Hz) are performed with modally reduced order components and measured or from elsewhere estimated external loads. Nonlinear dynamical phenomena are often completely left outside of this analysis scope, since project deadlines

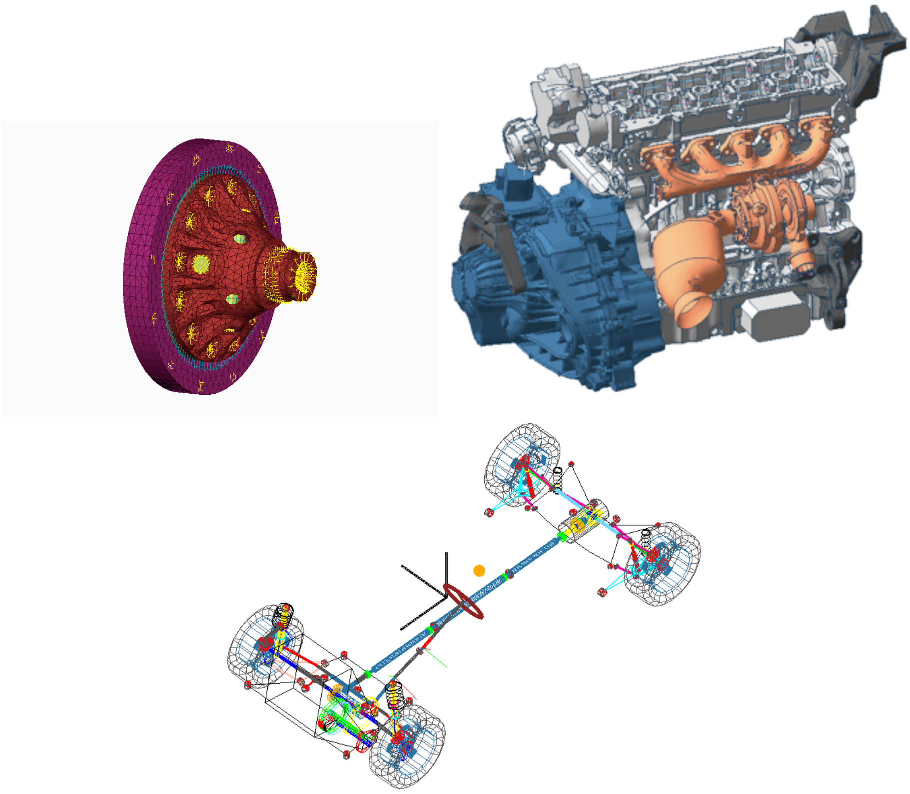

Figure 3: Examples of finite element and multi-body dynamic models from automotive powertrain applications. Individual figure scaling is used.

and designated analysis methods do not allow a more thorough investigation. For design analysis of vehicle driveability, handling, ride and durability, other constrained multi-body dynamical system models are built and used in simulations. These models consist of mostly rigid inertial components connected by primitive kinematic joints and discrete rotational spring elements, and are made with a clear focus on system responses in the lower frequency range of 2-20Hz (10-100Hz for durability with more included flexible components). Such complete vehicle models typically have a few hundred dynamical DOFs and are run on modelled test roads or chassis dynamometers for evaluation of system transient responses and extraction of the corresponding dimensioning component reaction loads.

In developing specific driveline technologies, subsystem design and calibration responsibilities are often given to an company-external supplier that needs to estimate the loads that their components experience during a lifelong usage. For example, the tightly integrated dual-mass-flywheel and clutch subsystems are known to be very central to the resulting torsional vibrations in the driveline [10]. They directly experience the peak loads of the pulsating combustion engine and provide multiple functionalities for reduction of downstream driveline vibrations. Consequently, few-DOF driveline torsional vibration models are developed for internal design optimisation, having more detailed models of the included arc-springs. Due to proprietary rights these models are usually not made available to the driveline system designer in time for design specification. Also, data driven *statistical* models exist and are used mostly within function development and design of control systems, [11]. These provide effective mappings of complex input output responses without having to model internal parts, or provide simpler models for real-time evaluation in control systems. Definite drawbacks are that data are needed first in order to establish the statistical models, which makes responses in new developed conceptual designs difficult to predict. The mathematical parameters used are often difficult to clearly interpret in a design modification situation, since they do not have independent coupling to component design parameters. In general, the major disadvantage of virtual methods is the usually quite large modelling errors that are normal for more complex system descriptions. This results in that, similar to with experimental methods, such virtual methods today are best used for verifying analyses and not conceptual design studies. Further references to relevant state of art methods are found in the attached *Papers A-D*.

2.3 Aim and scope

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 full system. 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 is flexible under loading and so is the rest of the car. The powertrain (including the driveline) interact with the rest of the car via connecting elements such as bushings, springs and dampers. The focus is here on the powertrain and its internal nonlinear connecting elements and assume that for the vibrations caused by the powertrain itself, the rest of the car behaves more or less linear. The main interest of this work is limited to stationary operating conditions, which is motivated by the focus on conceptual system design. The grand purpose of this work is to increase the good use of virtual simulations in the current automotive design process by providing efficient models and analysis tools. These methods should be valid for general application in nonlinear rotor dynamic powertrain systems and be shared by others in design process. Analysis tools should provide opportunities for better understanding of occurring system responses in order to remedy related problems by conceptual design, rather than by hardware trial-and-error. The virtual design process should complement the traditional automotive development process and generate useful information in time for important development decisions. The main goal is to find an efficient combination of practical modelling and analysis methods, which are further developed and modified to meet the challenging design situation that exists within automotive powertrain development. 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, emissions, driveability and durability.

Rather than proposing new variants of already existing and trusted methods, delicately selected combinations are instead implemented to address the specified research questions. Problems that depend on combinations of component details that are typically not available in conceptual models are left outside the scope of the work. Many real life vibration problems depend on details about component interactions and how small individual contributions are combined into significant disturbances. Since, the the number of possible variations of such cases is large, they are better treated individually, when they specifically occur during hardware prototype testing.

2.4 Research questions

The focus is put on virtual models and methods for conceptual design analysis and synthesis of nonlinear dynamical systems. The key issue in conceptual design is the model complexity. It needs to be simple to allow for extensive parameter studies within the fast pace of the design cycles. It needs to be accurate to capture system interactions that are likely to contribute to the sensitivity to parameter variations. With multiple nonlinearities it is important to include (at least) phenomenologically correct component descriptions that can interact during the simulation. The models searched for are ultimately parametrised using physical insight. The guiding principle is to keep models as simple as possible but as complex as necessary for sufficiently accurate prediction ability. The key phrase is thus minimum parameter system models, which involves components of minimal order and significant nonlinearities with as few physically based parameters as possible. This makes it practical to do rapid parametric studies, robustness evaluations, optimization and others that require a lot of evaluations.

The main research questions can be summarised, as follows:

- How to model a nonlinear rotor dynamic system under varying load and speed, to predict powertrain resonances that normally occur?
- How to synthesise linearly and nonlinearly behaving components into a system model of minimum order?
- How to support and interact with the existing development process?
- How to evaluate multiple system variant proposals under rapid conceptual design iterations?
- How to efficiently process large amount of simulated response data, to extract system characterising information?

3 Building blocks

The intent of this research work has been to develop system design analysis methods that are positioned (with an overlap) between traditional rigid-body system and structural component simulations. This is to fill the void between the two disciplines and better address recurring (unresolved) problematic nonlinear driveline responses that reduce system robustness. This section describes fundamental ideas and building blocks of the proposed design analysis methodology, which is summarised in section 4.

3.1 Conceptual design models

For the conceptual design of drivelines it is essential to learn about fundamental system resonance states and how they vary and possibly interact over the complete operating range. With such knowledge, qualitatively correct behaviour of new system design proposals can be understood and the most promising ones be recommended for continued development. This can be accomplished by selectively addressing only the most basic response types at times before conceptual design freeze, by using assemblies of simplified (geometrically de-featured or modally reduced) component models. This is meaningful as long as principal geometrical dimensions, large motion kinematics and significant load paths are preserved, as they often are most important for the system's qualitative nonlinear behaviour. By assuming that basic dynamical phenomena occurring in such simplified virtual system model provides valid information about the corresponding (fully detailed) real system's fundamental behaviour, makes it possible to investigate alternative conceptual solutions and substantiate the crucial design questions that will lead subsequent development efforts to success.

Robust design of nonlinear structures requires that many parameter value combinations are evaluated, due to the sensitivity to small disturbances and the large number of phenomena that can live in such systems. With assembled parametric component design models the available computer power can be used to efficiently test such system design variations, which adds significant value to the overall design process. Using simulated characteristics of a structurally simplified system model as idealistic design goals throughout the development process allow virtual methods to uniquely contribute to the design of the resulting physical system. Many other problematic responses that may occur in the fully detailed physical system are not included in the conceptual design analysis and must be solved in the usual (complementary) component design process. Moreover, utilising ideal circumstances of virtual simulations, and seeing them as assets in early developments rather than shortcomings in comparison with physical reality, enable precise extraction and understanding of the system characteristics, which are normally blurred by noise, imperfections and other uncertainties. For example, with fully known whitebox model and applied deterministic stimuli and accurate measured signals, where the only noise comes from finite precision truncations in numerical time-stepping and transient effects of those, the response analysis can be made arbitrarily precise (within the number of significant digits used). In conceptual design it is further motivated to restrict the analysis to selected cases where stimuli-responses are periodic over time. Thus evaluating component parameter variations in virtual system simulations, using trusted and practical structural analysis methods, facilitates that crisp and accurate system qualities can be revealed in conceptual system design analysis.

3.2 System modelling principles

As described in section 3.1, virtual system models with fewer geometric details than in a final analysis are used in early design phases to simulate fundamental linear and nonlinear system phenomena that are likely to occur in later physical realisations of conceptual design proposals. To obtain such a simplified driveline system model that is qualitatively valid over an operating range, it is important to include *large motion kinematics* and *correct load paths* for the relevant operating conditions. For this a flexible multi-body dynamic system model is used, which consists of separate *linear structural components* that are coupled by other significantly *nonlinear connecting components* (typically machine elements like bearings, gears, arc-springs, clutches, drive joints, splined joints, rubber mounts, etc.), see for example [12]. From experience in automotive engineering, non-robust system responses often relate to nonlinearities in joints rather than to intermediate linear structural parts. To quantify the absolute correct general behaviour of a nonlinear system by simulation is difficult and requires detailed models, much calibration work, etc. For conceptual system design analysis, a phenomenologically valid system behaviour can be obtained with schematic descriptions of many nonlinear components, preferably using only a few physically meaningful design parameters. Without nonlinear components, the simulated fundamental system response quickly becomes less relevant for capturing occurring problematic driveline responses.

To define and maintain subsystem modularity of a full powertrain system model and be able to modify the detail level of individual components, the *connecting interfaces* between the building blocks are critical. There are infinitely many possible interface definitions, but here the location of the attachment points between connected hardware components are considered the most useful divisors. Structural *interface nodes* are best located at points representative of the corresponding interface macro-geometry, preserving physical lengths, centre offsets, attachment foot-prints, etc. Apart from facilitating system requirement cascading down to subsystem specification, this makes sure that modelled virtual components fit as well together as their corresponding physical counterparts will do. Linear structural parts and nonlinear connecting parts can then be grouped into separate virtual powertrain subsystem models that are further interconnected to form *one system base-model*, which is compatible with agreed physical design and requirement verification responsibilities, etc. Individual connecting subsystem models can consist of a simple algebraic constraint or an entire multi-body system, but are always as equally important system building block as any other structural model. A further division of the subsystem models into *rotating parts* and *non-rotating parts* is useful for extracting reaction forces from the rotor system to its supporting structures for the subsequent component sizing process, etc. Similar to normal hardware based development testing procedures, new and existing component models can be connected into a general virtual prototype that allows new component design proposals to be efficiently evaluated in a full system environment. Depending on the current development phase and analysis question, individual refinements can be made from the single base-model, always with possibilities to resolve any model or result contradictions, which contributes to a common best understanding of the system.

Geometry is an important part of mechanical design and should be included in a structural system model. By utilising advanced capabilities of commercially developed mechanical design and modelling tools, such as parametrised solid geometries in hierarchical assemblies and automatic meshing with associative interfaces, it is possible to efficiently include and update *three-dimensional geometric* structural parts within rapid prototype design iterations. Since these software tools are broadly used within automotive industry it should be relatively easy to share component models between designing departments within a company, as well as, between external consultants and suppliers. In the resulting detailed solid finite element models, mass and stiffness distributions are well represented from first principles to capture geometrical couplings that often are part of a specific problem and its design solution. Larger structural blocks are simply formed by rigidly connecting coinciding interface nodes of parts that behave linearly together during system operation.

3.3 Balanced component reductions

In order to rapidly evaluate multiple conceptual design variant proposals, the assembled analysis models need to be both as simple as possible and sufficiently accurate to correctly capture qualitatively system resonances and their variation across the operating range. Thus, the included component models should be well balanced with respect to prediction accuracy and simulation speed, for multiple relevant operating conditions. Efficient state-space reduction methods can be used to selectively control model order within *a priori* specified error tolerance, for defined input-output relations. This makes it possible to build and keep one common and generally valid (as well as heavily overparameterised) system model that are used to generate multiple, individually balanced, conceptual system models for various specific design studies. The proposed conceptual design modelling approach is based on a well established process using finite element component models, modal reductions and multi-body system synthesis. This results in a large system assembly of interconnected linear and nonlinear components that is capable of capturing multiple real occurring dynamical phenomena, but becomes unpractical for rapid system design iterations. Therefore, to combine a generally valid base model with more efficient conceptual design models, additional reduction steps are performed. The overall reduction steps are shortly described, as follows.

Standard modal reduction. As mentioned in section 3.2, solid finite element models are used to form linear structural blocks that are the most heavily parametrised components of the system model assembly. Standard finite element solvers typically have a few popular modal reduction techniques implemented, like the fixed (Craig-Bampton) and free (Craig-Chang) boundary interface methods, see for example [13]. A common linear component reduction strategy is to include all eigenvectors with eigenfrequencies lower than three times the expected maximum excitation frequency that occur during response simulation. In structures with high modal density this results in many retained similar modes and a less efficient reduction. Using fixed interface mode synthesis further adds static interface mode vectors to obtain statically exact modelled attachment deformations. This is representative of multi-body simulation models used in driveline development projects, which perform well when run "as is" in a few verifying analyses, or several times with its structural components simply made rigid, as is common in vehicle simulations. However, to capture the fundamental elastic system response modes and learn how component design parameters influence a non-robust system response requires a more nuanced reduction approach, like the one possible with state-space reduction methods.

Generally balanced reduction. Reduction methods that consider defined stimuli-response relations are well established and used within the field of automatic control, but are not yet commonly applied to balance prediction accuracy and evaluation effort in large-scaled structural models [14]. These are typically formulated in first-order state-space form, with both input-to-state and state-to-output equations, as opposed to the second-order form without specific output definition that is primarily used within mechanical design. The main benefits of the state-space approach is that reductions can be done with *a priori* upper error bound and that the most relevant mode vectors are individually singled out for the specific problem. This offers possibilities for significant improvements of the standard modelling and reduction process, in which retained modes vectors are selected in chunks. To obtain a further general reduction (within the specified error tolerance) of a preceding Craig-Bampton reduction, a state-space method s applied with all component interface DOFs present in both defined stimuli and response sets. This is used to objectively balance prediction accuracy and simulation speed for different specific problems of the common general system model. For the most basic conceptual design analyses it is possible to make significant reductions still within a purposely selected error tolerance. This is reduction approach is exemplified in the appended *Paper B*.

Specific reduction. If more information about specific responses in the current system is available, yet another reduction step can be applied after standard modal and generally balanced reductions. This can be applicable when the system model has been assembled and simulated once, and the same set-up will be used again in another set of simulations. Alternatively, if additional system information collected from physical/virtual system/component tests are applicable to the model. This specific step can be done both with many reduction techniques, such as balanced truncation, modal dominancy, modal strain energy, etc. Read more about these methods in *Paper B*, or directly in [14] and [15]. In any case, the relevant extra information is used to establish minimal parameter system models that stay within the specified error tolerance for the specified transfer case.

3.4 Efficient response analysis

As described in section 3.1, a fundamental idea of the proposed design analysis methodology is to utilise the possibilities of virtual simulations to perform ideal experiments, with perfectly applied stimuli and almost noise free responses. The only error sources are the finite precision truncation error of time integration and transient effects from these (and possibly remaining initial conditions). This allows more precise information from a periodic stimuli-response test to be extracted than possible in real life structural tests. Automotive analysis engineers commonly use frequency response functions, FRFs, to diagnose problematic responses from measurements in performed physical tests. Methods used to extract the FRFs are well based in linear theory and have proven to work well in general real testing situations, [6] and [7]. Generalised FRFs contain much information about both linear and nonlinear system behaviours and can be used as indicators of multiple occurring response types. For example, linear resonances and anti-resonances manifest themselves as major peaks and troughs in the data [16]. Gyroscopic effects are seen as rotational speed dependences [17]. Nonlinear behaviours appear as deviations from the corresponding linearised system's FRF. A nonlinear primary response then show a deviation of the fundamental order, whereas a nonlinear secondary response shows a peak at a frequency that is a rational multiple of the excitation frequency, etc., [18]. A simplified system model can provide more crisp information about ideally occurring nonlinear responses if used in its full virtual domain, rather than one limited by real world preferences. Thus, if the trusted analysis methods are applied to fully known system models, with ideal excitation and under low noise conditions, the opportunities are good to further improve detection, location and characterisation of the occurring simulated responses. This provides unique information into the design process and can help to predict the most likely nonlinear modal interactions to occur in a later physical system realisation and, thereby, learn that one concept solution is more robust towards vibration problems than another.

The efficiency of modern computers, and available modelling and simulation techniques, makes it possible to perform many virtual experiments within a relatively short period of time. This is used to evaluate many alternative design proposals in time for more or less crucial design decisions and project deadlines. This generates large data sets that are difficult to investigate in all. Existing analysis tools often require much manual processing and interpretation, which creates bottlenecks in the development process. With a

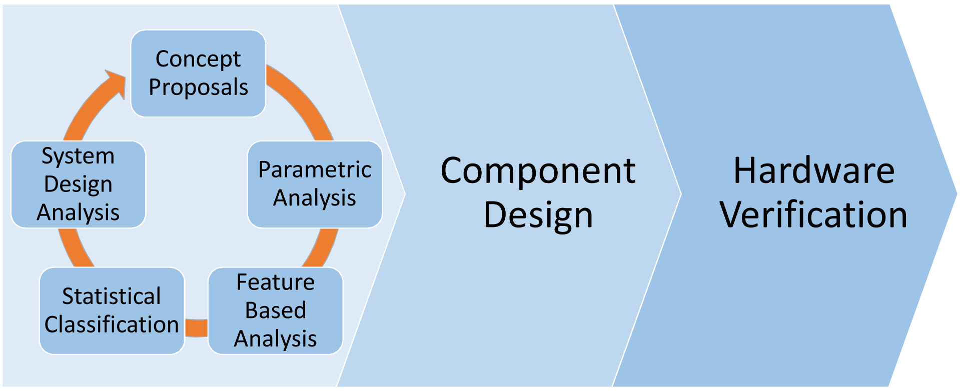

Figure 4: Overview of proposed conceptual system design analysis process (internal cycle) starting with *Concept Proposals*. Positive outcome leads in to traditional *Component Design* and *Hardware Verification* design processes.

good feature metric that consistently follow (at least) the qualitative interpretation of the practising analysis engineer, popular statistical methods can be used to automatically process and classify large amounts of simulated response data, see [11]. This can be an efficient help in the analysis work. The virtual low noise conditions are further expected to make the classification results crisper, in comparison to the corresponding real test situation. General statistical classification methods are the expected to more robustly distinguish between response types. This practical analysis approach is intended to mimic how an engineer works with established tools and use computer power to improve the quality of the results, as well as, increase the throughput of analysed data.

4 A conceptual design analysis methodology

The workflow of the proposed conceptual design analysis process and its sequential connection to the traditional driveline development process, are illustrated in Fig. 4. Short descriptions of each process step are given in the following sections, with more detailed application examples in the appended *Papers A-D*.

4.1 Concept proposals

In automotive industry, conceptual driveline design studies often start with a few new (or replacing) subsystem design proposals that are to be integrated into an existing hardware system solution, in a way that meets all project goals and requirements. In the earliest development phases, the new subsystems are not physically developed and mainly exists in the virtual world. At this time, many design parameters that significantly influence the system characteristics are still open for modification. At the end of conceptual design phase, the driveline proposal that appears to best fulfil given time, cost and technical requirements is likely selected for realisation and mass production. When a subsystem has been selected and decided, component design comes into focus using the last conceptual system status as prerequisites. The biggest chance to influence the system design is clearly before the subsystem selection is completed and this is primarily when the proposed conceptual design analysis process should be used. Thus, using the modelling principles and techniques described in sections 3.2 and 3.3, multiple conceptual system design models are put together. When specific conceptual design models are missing, existing component solution models can be modified and used to build the new virtual system prototype. Alternatively, phenomenologically correct analytical models, measured or estimated data can be used as component descriptions. It is most important to start simulating system responses at this time in development, rather than to wait until more component details are settled, in order to best contribute to the engineering system design process. The outcome of this phase of the virtual design analysis process is a set of different conceptual system design models, with an agreed set of design parameters, to evaluate and compare their qualitative system responses, as described next.

4.2 Parametric analysis

A selected set of critical (dimensioning) system operating cases is used to evaluate simulated responses of each modelled concept design proposal, under extensive model parameter variations. This is done to evaluate and compare performance and robustness between different conceptual design proposals, but also to find good component parameter combinations within each concept. To be efficient and keep strict project deadlines, each simulated variant is then simply checked for OK or not OK (NOK) system response values, ac-

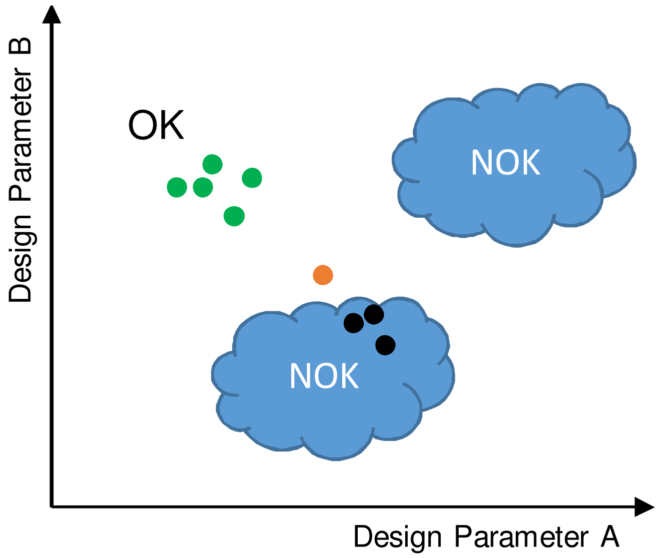

Figure 5: Principal illustration of an input design parameter mapping to OK (green circles in white areas) or NOK (black circles in blue areas) response samples. One sample (yellow circle in white area) exemplified an OK response that is considered too close to the NOK area.

cording to the relevant requirement set specification. If, for example, selected driveline structural vibration amplitudes are found less than a maximum allowable value, the design proposal is considered to be OK for the tested operating condition. And if too many of the evaluated vibration points exceed the requirement value, the design is considered to be NOK for the tested operating condition. From the many simulated parameter variations and the corresponding response evaluation, valuable information can be extracted for design reviews or any other technical discussion. For example a design parameter map illustrated in Fig. 5 can be used to imply design change consequences. At this time of development, it is considered most important to find design parameter settings that correspond to overall OK system responses, and less important to further analyse the variants that results in an overall NOK result. If at least one acceptable design proposal is judged to be OK (with some added uncertainty margin), that system concept proposal can be selected and ready to proceed with traditional component design and hardware verification processes. If instead a promising concept proposal is found NOK within the feasible parameter range, it becomes important to know more and learn *why* the response is NOK. Then, the proposed conceptual design analysis cycle (in Fig. 4) is continued with a *feature based analysis*, which is described next.

4.3 Feature based analysis

When there is at least one preferred conceptual design model judged to be NOK, in a parameter variation analysis across the available design parameter space, it is important to learn *why* this is so, in order to suggest a robust design solution to the problem. If, for instance, it is shown that the critical vibration corresponds to a resonant sub harmonic response that is due to a nonlinear interaction between load dependent fundamental system modes, it is easier to find an efficient design modification than if that information was not known. Therefore, in the *feature based analysis* step (in Fig. 4), new numerical experiments are set up and run for the concept proposals that are still of interest. The parameter combinations of critical responses are included in a new parameter study that now also include systematic variations of the system's operating parameters (speed, load, etc.) and external stimuli parameters (excitation frequency, mean and amplitude, etc.), to gather more system time-response data that reveal fundamental system characteristics. By applying a perfect periodic stimulus to the system model during its steady-state operation, and simulating its almost noise-free forced response until significant transients no longer are detected, accurate periodic responses can be recorded (although sometimes not in nonlinear systems). These time signals are processed into generalised frequency response functions (FRFs), which are compared to the corresponding ones from the linearised system. A manageable number of extracted response function are individually inspected, qualitatively interpreted and classified by a practising engineer, using calculated response feature metric values and a set of rules-of-thumb criteria, as exemplified in the appended *Paper C*. This analysis process step hopefully results in a better understanding of the NOK response and a set of generalised FRFs that can be used to map the variation of fundamental system resonances across the operating range, as well as, calculated feature metric values and their assigned response types. Also a complementing possibly large set of unclassified simulations that contains more system information remains, but is unpractical to process manually. A solution to this problem is addressed in the following section.

4.4 Statistical classification

After a feature based analysis, a set of time-responses and their corresponding calculated feature metric values and assigned response class labels are available, along with a possibly large set of other unprocessed simulations. Statistical tools can then be used to automatically sort new data into response classes in a procedure known as supervised learning. This requires that related feature metric values and corresponding class labels that exemplifies the classification are given. In the *statistical classification* process step (in Fig. 4), a supervised learning is first performed on the available training set. One generally applicable and well established type of classification method is the *support vector machine*, which is exemplified in the appended *Paper C*. Estimations of how accurate the trained classifier would perform on new data are indicated by commonly calculated cross-validation scores. The classifier can then be used to automatically process feature metric values calculated from the other large data set (without human interaction) and, thus, help the engineer to sort simulated responses into categories. The outcome of this analysis process step is that all simulated responses are automatically processed and sorted into qualitative classes. This is a good set-up for a the next system design analysis step, as follows.

4.5 System design analysis

From the supervised classification step, the full analysis data set (parameter values, excitation and response time-signals, FRFs, calculated feature metric values, etc.) from all cases in the simulated parameter variation experiments are sorted into qualitative response classes (aperiodic, quasi-linear, sub and super harmonic nonlinear, odd and even nonlinear, etc.) and available for the actual *system design analysis* process step (in Fig. 4). This means that the practising engineer are presented with a good (but preliminary) overview of the different response types found in the full simulation set. From this smorgasbord of available classes, he/she can selectively focus the coming analysis on the most interesting cases for the current design issues. This will give a better understanding of the underlying nature of the system and plausible explanations of problematic responses, as well as lead to improved concept proposals and truly effective system design changes to recurring problems, in a new process cycle.

5 Summary of appended papers

Paper A: *Driveline model calibration and validation in an automotive 4-cylinder Diesel application.* A prototype of a complete front-wheel-drive powertrain is tested in a physical rig and a nonlinear torsional resonance is identified in measured response data. A set of previously specified conceptual modelling principles are realised into a general flexible multi-body system model to capture fundamental powertrain resonances and their qualitative variation over load and speed operating ranges, in order to improve the good use of virtual simulations in early design phases. A small parameter study using the computational model shows how parameter settings of selected components influence the system normal modes. After performing calibration and validation on complementary sets of measured data, a single set of model parameter values captures qualitatively correct nonlinear system dynamic behaviours at multiple load levels and operational speeds. The study shows that the developed system model, and thus the chosen modelling approach, is capable of capturing load and speed dependent system dynamics of a real driveline in operation. The sensitivity of system responses to flywheel arc-spring design parameters is concluded.

Paper B: *Efficient Component Reductions in a Large-Scale Flexible Multibody Model.* The implementation of two state-space reduction methods into the normal workflow of computational software NASTRAN and ADAMS is described. Four alternative modal reduction methods are applied to selected major structures of the powertrain model used in *Paper A*. Two of these methods consider general input-output relations that can be efficiently applied to separate components to strike a good balance between prediction accuracy and computational effort for general operating conditions. System simulations are performed across the operating range and powertrain responses related to vehicle noise and vibrations are evaluated for each reduction variant. The prediction accuracy, as well as, reduction and response simulation times for different model orders are considered in the study. It is concluded that the implemented reduction methods, *Balanced Truncation* and *Modal Dominancy*, each deliver improved efficiency by providing at least equivalent prediction accuracy as standard methods to a significantly shorter reduction and simulation time.

Paper C: *Feature-Based Response Classification in Nonlinear Structural Design Simulations.* A novel conceptual design analysis approach is presented that is intended to help the practising engineer to process large amounts of virtually generated data into qualitative response categories. The main idea is to apply trusted analysis methods from experimental structural dynamics to constructed virtual experiments, with ideal multi-level multi-frequency stepped-sine excitation and low simulation noise, to extract precise multi-frequency response functions of operating flexible multi-body system models. An order-based feature metric compares the response functions of corresponding generalised and linearised systems for a nonlinear classification using qualitative analysis rules-of-thumb criteria. A statistical support vector machine is then trained to automatically classify new data sets from extensive design parameter variation simulations. The conclusion, based on two separate training study examples, is that the proposed analysis and classification approach works well for its intended purpose.

Paper D: *Comparison of stimuli for nonlinear system response classification.* Alternative stimuli functions are evaluated with respect to their performance and overall efficiency in the feature-based response analysis and classification methodology proposed in *Paper C*. The reference multi-level multi-frequency stepped-sine periodic stimulus function is known to provide much system characterising information from a single test-sequence. Its major drawback is the long total simulation time needed to obtain periodic responses for an accurate subsequent frequency response analysis. The robust and fast pseudo-random phase multi-sine variants are both potent alternatives for fast estimation of frequency response functions and related nonlinear and noise variances. Both multi-sine variants provide less system information than the reference stimulus does and specified fast variant nonlinear classification procedure shows a high sensitivity under low noise conditions. Two alternative feature metrics are proposed for improved multi-sine applicability to automated nonlinear response classification. All three stimuli functions are compared in a rotor shaft model application and are found good for conceptual design characterisation and classification. Based on individual characteristics, it is recommended that they are used for slightly different analysis purposes and in combination for best overall result.

6 Concluding remarks and future work

The main purpose of this work has been to develop modelling and design analysis tools that will lead to an increased and better use of virtual simulations in early development phases. The result is a conceptual design methodology with focus on fundamental system and structural dynamical responses. The work has progressed along three main paths that each significantly contribute to the resulting proposed conceptual design analysis methodology.

First, improving the *prediction accuracy* of standard simulation models with respect to nonlinear dynamic phenomena. This is crucial for capturing and understanding problematic system responses that occur in the powertrain. It is accomplished by including significantly nonlinear connecting parts, acting between linear elastic structures of correct solid geometry, into a flexible multi-body rotor dynamic system with large motion kinematic constraints. The study performed in *Paper A* confirmed that the chosen modelling approach can capture real nonlinear resonance phenomena with strong dependences on system load, speed and damping. Although one can argue that the same phenomena can be adequately captured by a single DOF nonlinear analytical model, a major benefit of the more complex model is a more general validity, with multiple possible system configurations and nonlinear response mode interactions that can be further investigated. Another advantage is its close connection to component design models and physical reality, for efficient geometry updates and physical interpretations. Included component design parameters can be individually evaluated with respect to conflicting problematic responses and used to balance resulting system qualities. Further, using the corresponding physical interfaces as divisors in component synthesis makes it easier to interact with the evolved hardware development process, with respect to subsystem requirement setting, etc. A system model that allows separate component replacements and discretisation levels, makes it easier to share common parts between projects and development phases, in order to maintain a complete and updated system assembly. These analysis aspects motivate the need for required extra system modelling resources.

Secondly, improving the *simulation efficiency* of general multi-body dynamic models used in conceptual system design. This is critical when including detailed finite element models in large multi-body dynamical systems. The resulting system model order needs to be in balance with the required prediction accuracy. The implemented state-space modal reduction methods evaluated in *Paper B* add improved functionalities into the normal modelling workflow and are considered better apt for use in early design phases. The possibility to make significant component reductions, within a specified error tolerance, is crucial for the chosen modelling strategy. Then, one common (overparameterised) system model can be built, with general validity and updated geometries, and used to generate appropriate few-DOF system models that are used in different specific analyses. Since all specific system models share a common base, it is possible to resolve any apparent response conflicts. Individual component design proposals can also be verified altogether in a full system simulation. State-space reduced modal components are surprisingly useful in many modelling scenarios, e.g. as an assembled linear flexible body that can be updated with the appropriate prediction accuracy for the pending task.

Thirdly, improving the *response evaluation efficiency* of extensive parameter variation simulations. Considering the circumstances of automotive development, a two step conceptual design analysis methodology is proposed in *Paper C* and further improved in *Paper D*. Starting with simulated parameter variations of multiple conceptual design models that are quickly checked for OK or NOK responses. This implies the qualitative robustness of competing system proposals and is the minimum amount of information required for making a first concept selection. For a better understanding of specific NOK responses, the analysis can (optionally) continue with a second step where fundamental system characteristics are sought. Then, ideal virtual simulations and efficient feature based analysis are used to generate and automatically process data, to extract unique system characterising information for use in the design process. Supervised statistical methods were used to automatically process and sort responses into qualitative categories, in order to stay transparent and always keep the engineer in the analysis loop. This automated analysis and classification approach is considered promising for use in conceptual design phases and an interesting topic for continued developments.

Future work should involve applying the proposed methodology to appropriate development projects to pick up relevant analysis questions and perform model validation on real problem data. Mapping of system resonances across the operating range will help to explain occurring powertrain responses and design more robust future drivelines. Questions remain about how the classification approach performs on larger data sets from multiple input and output tests? How does feature metric performance scale with a greater number of response modes? Can multiple feature metric combinations be found to robustly indicate and discriminate between specific application error states, like driveline booming or gear rattle? How to robustly classify random response signals with very low noise level? Much applied work are likely needed to find ways to proceed with such questions.

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