Chapter 1

Introduction

Mechanical design engineers are being presented with ever more powerful and capable analytical design tools. This is principally driven by continuous improvement in the price-performance ratio of digital computer systems and the strive for optimised designs with lower safety factors and increased reliability. The competitive market of today however demands these optimised designs to be backed by extensive product development and testing. Lund and Donaldson [42] recognised the important role of testing in design, especially laboratory testing of full scale prototypes or components. The same authors stated: "The most rapid advances in testing technology in recent years have occurred in the area of service history simulation." The importance of this ability to reproduce actual measured service conditions in a controlled laboratory environment is further stressed by Zomotor, Schwarz and Weiler [63] for evaluating passenger car ride comfort and fatigue strength of vehicle components. Similar views have been expressed from various fields in industry ranging from aerospace [33] [27] to agriculture, [30]. The numerous reports on varied applications of laboratory simulation testing and the importance thereof warrant further investigation.

1.1. Overview

Dynamic response reconstruction, also termed service load simulation testing, or service history simulation [42], enables the replication of actual service response data on a dynamically loaded test structure in a laboratory environment using multiple axis computer controlled servo-hydraulic actuators. Service load simulation testing offers the only method of reliably conducting interactive multiple-axial fatigue tests.

This thesis forms part of a research programme to further improve a time domain service load simulation system developed by Raath [52] and implemented into a multi-axis test and control package (QanTiM) [34]. Two global aspects are addressed, firstly the effect of varying input parameters and operating procedures for the existing linear techniques, and secondly the inclusion of non-linear modelling elements within the existing linear package.

1.2. Historical profile

The field of simulation testing is relatively new, driven mostly by the automotive industry since the early 1960's. The use of servo-hydraulic actuators to simulate dynamic input loads for vehicle suspension systems was reported in the mid 1960's by Hodkin [31]. Scott [57] reported a road simulator erected in Coventry in 1967 that made use of an open-loop simulation system similar to a gramophone player. A six-foot diameter rotating table was "paved with bits of shattered, toughened-glass windshield to represent cobble stones", four transducers positioned on radial arms over the rotating surface measured "wheel inputs". Displacements recorded by these transducers were amplified by an electronic control system and applied to the vehicle's wheels by means of four vertical servo-hydraulic actuators.

A positive step towards simulation was reported in 1968 by Barrowcliff and Ehlert [3] in the paper: "Full Scale Road Simulated Endurance Test". The authors recorded the vehicle's wheel acceleration responses during normal driving conditions. In the laboratory these measured accelerations were integrated twice to obtain displacement drive signals for the servo-hydraulic actuators of the road simulator. A more direct method for finding displacement drive signals for road simulators involved road profile measurements, typical examples were documented by Engels [25] and Whittemore [62]. The geodetic road profile measurement apparatus presented in 1968 by Engels proved accurate, but extremely time consuming. The "General Motors Road Profilometer" as presented by Whittemore in 1972 measured the relative displacement between the road surface and the moving vehicle. These dynamic displacement responses were used, along with an analytical model of the vehicle, to calculate drive signals for a servo-hydraulic road simulator.

In 1972 Dodds [23] proposed a technique in which a dynamic mathematical model of the test system (test specimen and rig) is used to calculate actuator drive signals from service measured responses. Dodds made use of frequency domain characterisation techniques to derive a Frequency Response Function (FRF) of the test system. This model was capable of predicting actuator displacements as a function of measured road responses [21][22]. This frequency domain analysis, later also proposed by Craig [19], paved the way for development of advanced service load simulation systems such as the "Remote Parameter Control" (RPC) by MTS Systems Corporation (USA) and the "Iterative Transfer Function Compensation" (ITFC) method by Schenck AG (Germany). These systems set the standard for simulation testing and are employed world-wide in various sectors of industry.

A recent development in simulation testing was introduced in the PhD dissertation by Raath [52] in 1992 titled "Structural Dynamic Response Reconstruction in the Time Domain". This method was implemented into the QanTiM [34] multi-axis time domain based test and control package. The time domain promises various advantages over the frequency domain techniques, which will be briefly discussed in Section 1.4, yet the principal operation proved similar to that of methods developed in the frequency domain. This basic operation and philosophy is discussed in the next Section.

1.3. Principles of structural dynamic response reconstruction

Over the past two and a half decades the accuracy of simulations has improved greatly due to the use of closed loop computer controlled simulation systems and an understanding of the dynamic relationship between the actuator input and the response transducer output signals [23][19][51]. Present response reconstruction techniques are generally governed by the following four steps.

1 Measurement:	The structure to be tested is instrumented with suitable transducers, and the response under operational conditions recorded.
2 Identification:	The instrumented structure is transferred to the test laboratory and placed on a servo-hydraulic test rig. Synthetic drive signals are used to drive the rig and subsequent responses are recorded from the same transducers used for the operational response measurement. The known input-output data is used to calculate a dynamic model for the complete system. (i.e. rig, controllers, test structure, etc.)
3 Linear drive :	The measured field responses are passed through the dynamic model to find actuator drive signals, which when applied to the test rig should force the same measured responses.
4 Iteration:	Due to inherent rig non-linearity, an iterative procedure around this first approximation finally yields accurate simulation results.

1.4. Frequency vs. time domain

The operation of systems in the frequency and time domain is, from a user point of view, very similar. The frequency domain however boasts a set of well-developed modelling techniques applicable to dynamic response reconstruction. This poses the question why a time domain simulation system was developed considering the long standing standards set by its frequency domain counterparts? Various discussions on the advantages, and disadvantages, of time domain modelling are found [28][49], most relevant is the one presented by Raath [52].

In general it has been shown that the newly developed time domain techniques have some principal advantages over its frequency domain predecessors. These advantages include shorter identification time [28], fewer iterations to convergence and, more important, the time domain techniques are capable of handling offsets and low frequency trends with ease. Frequency domain methods on the other hand have difficulty simulating offsets, and low frequency, high amplitude behaviour of the test specimen. Offsets in the desired response data coincide with non-zero mean structural stresses, whereas low frequency, high amplitude loading causes high peak stress levels within the structure. Inaccurate simulation of these mean stresses and low frequency, high amplitude stress conditions is detrimental from a fatigue analysis point of view. On the other hand, the main disadvantage of the time domain is the requirement of having to specify the structure and order of the dynamic system prior to the identification process. This problem has been overcome by using a generalised parametric time domain model description combined with a state-space formulation.

1.5. Dynamic system identification

The identification, more correctly, dynamic system identification, is the most significant phase within the response reconstruction framework. It is the platform on which response reconstruction techniques have been built and facilitated the quantum leap from the open loop gramophone system to present-day sophisticated commercial simulation systems. Dynamic system identification involves constructing a mathematical model of a dynamic system using measured input and output data from the system. System identification has found application in an extremely wide field covering engineering, socio-economics, ecology and medicine, to name but a few.

1.6. The inverse dynamic model

Most applications of dynamic system identification are conducted so that the system outputs are modelled as a function of the system inputs. An inverse dynamic model is however a requisite for response reconstruction. Here the system inputs (actuator drive signals) must be dynamically modelled as a function of system outputs (transducer responses from field measurements). Inversion of the dynamic model is however not trivial since the inverse model is frequently found to be unstable. Various inversion methods are presented for both the frequency and time domain [23][19][34][51].

1.7. Operational research into time domain application

Frequency domain methods have been in use and under development for more than two decades. In this period a wealth of knowledge and experience has been gained from its use on many service load simulation test rigs throughout the world. On the other hand, the time domain state space methods to date not have had this exposure simply because of its recent development.

Because of the limited application experience of time domain methods, operating procedures and optimisation of input parameters for the existing linear QanTiM system were researched empirically using various practical single and multiple-axis test rigs. The first aspect investigated was the effect of various band limiting filter operations on simulation results. This was followed by research into the optimal frequency content of the synthetic identification excitation signals. The concept of split spectra modelling was also investigated, where the broad spectrum dynamic behaviour of the system is split and modelled by a combination of narrow frequency bandwidth time domain models.

The experience gained during this research paved the way for further experiments and produced a set of guidelines for the practical implementation of QanTiM for various test systems. These guidelines include filter specifications for desired response data as well as synthetic identification data. Guidelines for creating optimal synthetic identification signals have proved valuable in multiple-axis test applications. Similarly split spectra modelling showed potential in rigs with dominant resonant behaviour.

1.8. Non-linear implementation

The linear time domain QanTiM techniques proved successful in simulating the dynamic response of most practical test systems. In a few isolated cases however the response of a system could not be simulated. Various possible reasons for poor simulation results were suggested including, static and dynamic non-linear system elements, rig resonance problems, numerical instability due to model inversion, orthogonal load paths between actuators and transducers, physically unrealisable response data (PUD), poor rig coherence, etc. Non-linear elements within the test system (springs, dampers, friction, servo-hydraulics, etc.) may be a likely cause of poor modelling and simulation results.

It was thus proposed to complement the linear time domain techniques by implementing non-linear modelling capabilities within the existing time domain techniques. A non-linear system identification technique well suited to response reconstruction, yet capable of seamless integration with the existing linear package was needed. An emphasis was placed on finding a black-box type model which is easy to use and requires minimal structure definition prior to identification.

The field of non-linear system identification, although relatively new, has been well researched, especially under the guidance of Billings [5][6][7][8] [14][38]. Yet a coherent body of economical, well tried and widely applicable non-linear identification techniques does not exist. Furthermore, to the author's knowledge no attempt has been made at identifying a non-linear inverse model, as required by response reconstruction.

A literature survey revealed various non-linear modelling techniques which showed potential for implementation into dynamic response reconstruction. Several of these methods were implemented, and in certain cases adapted by the author. The applied system identification techniques were verified through testing, firstly in a normal sense to evaluate non-linear modelling capabilities and secondly for application in response reconstruction where an inverse model was required. This process showed a group of polynomial non-linear auto-regressive exogenous input (NARX) model formulations as presented by Billings [5] to be ideally suited. The author subsequently developed non-linear simulation algorithms and an associated condensed non-linear model description for multiple-input-multiple-output (MIMO) systems.

The result was a set of system identification routines capable of modelling severely non-linear dynamic systems, and yet requiring minimal user input or knowledge of the system. However, the non-linear structure (that is linear, quadratic, cubic, etc.) within the system must be estimated prior to identification. The developed NARX routines are capable of both normal, and inverse dynamic non-linear modelling. Evaluation of the NARX system is presented for both synthetic and practical systems, revealing certain limitations:

- No procedure capable of practically detecting non-linearity within a servo-hydraulic test system could be found. The only indication of non-linear behaviour was thus a comparison of linear and non-linear simulation results.
- In the case of large MIMO systems the algorithms proved taxing for current computational capabilities.
- Application proved limited since the implemented non-linear algorithms showed some inherent stability problems, which were accentuated in the inverse model.
- Polynomial non-linear techniques proved ideal to facilitate ease of use and convenient integration with existing software, but may not be completely relevant for modelling vehicle dynamics. (A typical suspension element such as a jounce bump can only be modelled using a discontinuous non-linear technique.)

The NARX formulation showed potential as a general modelling and simulation tool, especially if combined with frequency splitting techniques.

1.9. Document overview

Only the most relevant theory is included in the body of the thesis, with more detail contained in the appendices. The thesis is presented in two parts, the first part covering empirical research into improved response reconstruction. Aspects such as rig repeatability, simulation bandwidth and split spectra modelling are introduced. The investigation into application of non-linear time domain techniques is presented in part two. As part of the literature survey, system identification theory is introduced in chapter 4 for linear systems, and expanded to non-linear systems in chapter 5. Chapter 6 shows various case studies of implementation of non-linear techniques. Appendices A through D contains the detail of the literature survey as presented in chapters 4 and 5. A summary of condensed NARX Matlab 'toolbox' of functions is presented in Appendix F. A brief description of QanTiM is presented in Appendix G