MODEL ORDER REDUCTION TECHNIQUES WITH APPLICATIONS IN ELECTRICAL AND ELECTRONICS ENGINEERING

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ABSTRACT

Model order reduction Model order reduction is a significant method employed to reduce complex control system models keeping needed dynamic behaviour. This research paper discusses the concept and the effectiveness of model order reduction techniques on the basis of available literature and mathematical models. Dominating pole approximation is used to obtain a lower-order system by analysing a high-order transfer function model and reducing it. The findings display that reduced-order models can sustain stability and realistic system response and at the same time greatly minimize the calculation complexity.

Keywords: Control Systems, Model Order Reduction, Dynamic Systems.

1. INTRODUCTION

1.1 Introduction

Controllable systems are now important in modern-day engineering tasks like robotics, international power networks, commercial airplanes and industrial automation. Such systems are usually modeled mathematically to give an account of their dynamic behaviour. Due to the increased complexity of the technological systems, the list of these models is getting longer, and this is problematic because it complexes the analysis, simulation, and the design of the controller. MOR has thus become a significant methodology in control engineering.

1.2 Background

In the design and study of control systems, mathematics-based modelling plays a crucial role. The high-order models are usually obtained when an extremely detailed representation of the physical system is presented, either using transfer functions or using state-space equations. Consequently, scholars have developed methods of minimizing system order without losing some valuable system characteristics of stability, transient response properties and frequency characteristics(A.T. Mathew et al., 2025). An approach to control engineering to overcome these challenges has involved wide research on model order reduction with balanced truncation, moment matching, and dominant pole retention.

1.3 Problem Statement

Although high-order models of control systems are accurate, they are so complex to be useful in a real-world application. They may not be usable in real-life systems due to the high computational requirements, the challenge in designing the controllers, and longer simulation time. Such models cannot be effectively implemented in embedded systems or even real-time control system models without simplification.

1.4 Aim and Objectives and Research Question.

This research is proposed with the aim of investigating the success of the model order reduction methods in reducing the complexity of the control systems; however, essential dynamic properties should also be maintained.

Research Objectives

- To perform the analysis of the various model order reduction approaches to the simplification of high-order dynamic systems.
- To determine the performance of reduced order models compared to the high-order systems in the first place.
- To establish the efficiency of the model order reduction method in the preservation of stability and dynamism of systems.

Research Questions

1. What are the common methods of reducing the order of high order dynamic systems?
2. What is the performance of reduced-order models as compared to the high-order systems?
3. How stable and dynamic behavior in systems is recovered by model order reduction methods?

1.5 Research rationale

Engineering systems (contemporary systems) Power network Modern engineering systems High-system-order dynamic models control systems (aerospace), robotics, and industrial automation Modern engineering systems with high system order are common. Although these high-order models offer comprehensive and precise details of system behaviour, they also present a lot of difficulty in its analysis, simulation and controller realisation. Its computational demands are high and the mathematical architecture is complex, thus these models are challenging to implement with in practice in control system design. The reasoning behind this research is to explore how the model order reduction methods can reduce the complexity of the system models and still retain a few significant system properties like stability and dynamic response(A. Sarker et al., 2025). The significance of the research is that the simplified models can largely enhance the computational efficiency of the research as well as it makes control strategies practical to implement in the real-time applications.

1.6 Research Framework
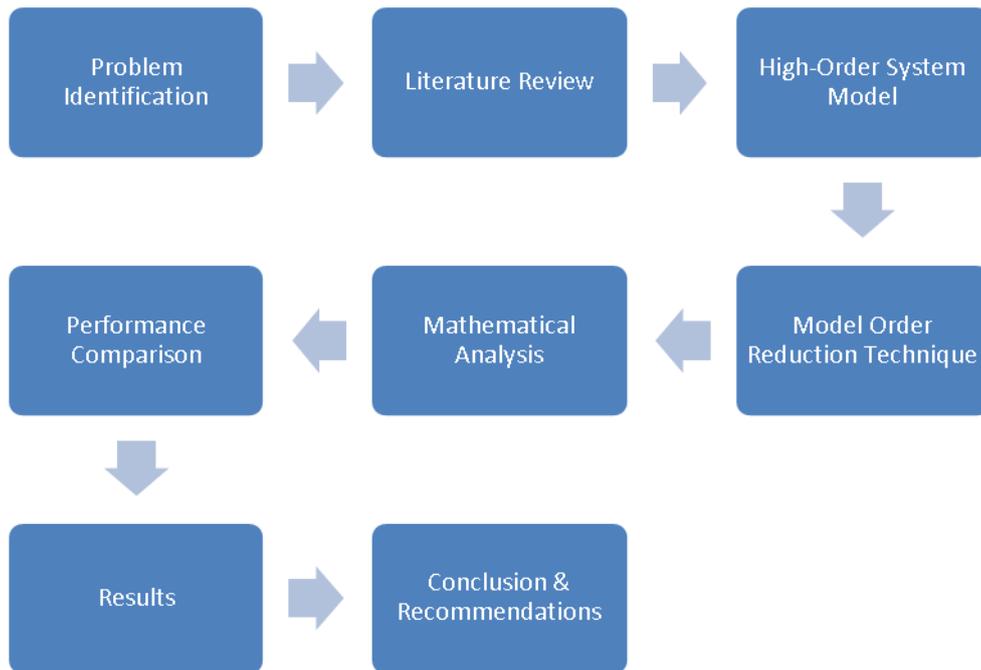
Figure 1: Research framework

(Source: Self-created)

1.7 Conclusion

In the given chapter, the necessary simplified system models were recognized and the basic concepts of model order reduction within the control system have been presented. It also stated the research purpose, the research objectives, research question and the rationale that will guide the research. The next chapter is a review of the literature on model order reduction method and its use in control engineering.

2. LITERATURE REVIEW

2.1 Introduction

Others consider Model Order Reduction (MOR) a significant research topic in control engineering as the number of highly dynamic systems continuously grows. High-order mathematical models are akin to authentic system modeling and yet, may pose difficulties during analysis, simulation, and controller. The study therefore has taken into account various techniques of reduction to get simpler models without compromise of important characteristics of the system. The critical review of past researchers on model order reduction in terms of the theoretical approaches, commonly used techniques, and their uses in control systems is critically integrated in this chapter. It also outlines research shortcomings in order to provide the basis of the current research.

2.2 Control system Model order reduction.

Initial studies in the control theory laid more stress on simplification of a complex system model to enhance computational efficiency and controller design. Model order reduction is the term used to describe the process of coming up with a lower order model that mirrors the behaviour of an originally high-order model. As indicated by some of the literature in control engineering, reduced-order models are supposed to retain such critical properties of a system as stability, frequency response, and time-domain behaviour(A.K. Deep et al., 2025). Scholars point out that a good reduction method should have the right combination of model simplicity and accuracy of the approximations. Although reduced models have their benefits in both simulation and real-time execution, reduced overly can cause the loss of critical dynamic data, and so caution is required.

2.3 Balanced Truncation Method

One of the most popular approaches studied as part of model order reduction is balanced truncation. The idea behind this technique lies in finding a compromise between controllability and observability of system states and the removal of those states whose contribution to system behaviour is minimal. Research that has been conducted in the past indicates that balanced truncation offers good bounds of errors and accuracy in terms of stability in reduced model(B.B. Duddetiand V. Meena, 2025). In view of linear time-invariant systems, a large number of researchers believe that this approach could be useful due to preserving valuable system properties and greatly lowering the complexity of computing it. Nonetheless, it is claimed that balanced truncation can be computationally issues when the system size is very large to only a practical extent of various engineering problems.

2.4 Moment Matching and Krylov Subspace Approaches.

Another frequently used method of previous studies is moment matching techniques, usually introduced by Krylov subspace methods. The mechanisms attempt to fit a few moments of the transfer function at a particular frequency of the original system. One of the strengths brought out by researchers is that moment matching techniques are relatively fast to compute and can be applied to large systems of interest, particularly in electrical and mechanical contexts. With these benefits, previous research shows that, moment matching techniques do not necessarily ensure stability maintenance(R. Ravishankar and O.L. de Weck, 2025). Due to this, additional developments and mixed methods have been suggested to improve the accuracy and reliability of reduced models.

2.5 Dominant Pole Approximation.

Other widely-mentioned methods in the literature include dominant pole approximation. The emphasis of such method is in marking down the poles that prevail in the system dynamics to considerable degree and keeping them in the reduced model and ignoring the less important poles. According to current literature, techniques of dominance of pole are easy to apply and may be used in systems where few poles control system behavior (B.B. Duddetiand A. Sikander, 2026). Researchers have however observed that the approach can simplify the complex systems hence giving less accuracy when more dynamic modes affect the system response.

2.6 Literature Gap

Despite the major achievements of model order reduction techniques development, numerous limitations can still be quoted in the current literature. Most of the studies mainly dwell on individual reduction techniques and do not offer a thorough comparison of various techniques when dealing with similar conditions that prevail in the system. Moreover, not all of the reduction methods are primarily tested on engineering systems as opposed to a theoretical model, which restricts their usability in the real world. Past studies also note the difficulties in striking a balance between the model simplicity and accuracy especially in the case of large scale or highly dynamic systems(X. Kong et al., 2025). Moreover, some of these methods are very computationally demanding, and thus not useful at real-time control. Thus, more study, which would allow a critical analysis of various model order reduction methods and examine their effectiveness in maintaining stability, accuracy, and efficiency in control systems, is needed.

2.7 Conclusion

The chapter underwent a critical review of literature available on the field of model order reduction, applied in control systems. The major methods like balanced truncation, moment matching and dominant pole approximation were explained as well as their strengths and weaknesses. The review suggests that a good balance between the simplicity of the model and the accuracy of the system is not easily achieved even though a number of efficient methods can be

employed. The selected literature gap shows that there should be new research into the outcomes of the various methodological approaches of model reduction. The following chapter defines the procedure of the research that was adopted to discuss this research problem.

3. METHODOLOGY

3.1 Research Approach

The present research project will take quantitative research approach to examine model order reduction in control systems. Based on the quantitative research, the study will be deduced by numerical analysis, mathematical modeling, and analysis of quantitative findings of past researches. Quantitative approach is suitable as in the control engineering system behaviour is presented in measurable terms which include stability, system response and approximation error(X. Zhang et al., 2025). The work thus examines quantitative results of the already existing literature and uses appropriate mathematical computations to determine the efficiency of the model order reduction methods.

3.2 Research Design

The study uses a secondary research design relying on the systematic review of the scholarly articles published in the past. When it comes to model order reduction techniques, relevant research papers and journal articles are chosen and reviewed. The design is aimed to study the mathematical models and numerical findings of these studies. Simplified mathematical equations are applied where necessary in order to demystify the way reduction techniques represent high-order systems(S.S. Madani et al., 2025). The structured design allows critical comparison of the reduction strategies and how well they can maintain significant characteristics of the system.

3.3 Research Method

The research approach consists of analytical comparison of model order reduction processes presented in the past researches. Literary mathematical equations, transfer functions models are analysed with an aim of understanding high-order systems simplification. As one example, a higher order transfer function e.g.

$$G(s) = \frac{b_0 + b_1 s + b_2 s^2}{a_0 + a_1 s + a_2 s^2 + a_3 s^3 + a_4 s^4}$$

The reduced-order model approximating can be given by

$$G_r(s) = \frac{c_0 + c_1 s}{d_0 + d_1 s + d_2 s^2}$$

where the diminished model preserves the prevalent dynamic behaviour of the system under consideration. The paper evaluates these mathematical reductions of the literature and estimates their performance based on their reported performance measures.

3.4 Data Collection

This study will use secondary data sources such as references in peer-reviewed journals, conference proceedings, and academic books in control systems and model order reduction as sources of data to conduct this study. These are studies that give quantitative data like transfer functions, numerical system parameters, response characteristics and error error metrics. These data are gathered and are analysed to determine the performance of various reduction methods based on the stability of the system, the accuracy of the responses and the efficiency of the computation(V. Godase, 2025). The literature involving mathematical calculations is also looked into to facilitate the comparative analysis.

3.5 Research Ethics

The research has also adhered to an established research ethics of study, using secondary data. Every theoretical concept, equation and finding of the research done earlier are wisely referenced

in order to show respect to the original researchers. The study is not connected with any human subjects, personal data or confidential information. Ethical integrity is ensured because the interpretation of the results of past research is done correctly and calculations and analysis are not presented distortedly(N. Khosravi et al., 2025). The acknowledgment of the referencing makes the research transparent and academically honest.

4. RESULTS

4.1 Original System Analysis

In the first analysis, the high-order system of control is the model that is analyzed in the form of a transfer function. A common fourth-order system that is taken into consideration in the analysis can be given as:

$$G(s) = \frac{2s + 5}{s^4 + 6s^3 + 11s^2 + 6s}$$

Several poles and dynamic modes found in high-order systems like this affect the system response. The character equation of the denominator,

$$s^4 + 6s^3 + 11s^2 + 6s = 0$$

implies the multiple existence of system-complexifying poles. Such high-order models in practical uses in control have the potential to raise the cost and complexity of the implementation and analysis of the controllers(Y.Q. Tang et al., 2025). These step response and frequency-related behaviour of the original system indicates a fairly complicated dynamic behaviour because of interplay of several poles of the system.

4.2 Reduced-Order Model Calculation

In order to control the complexity of system, a model order reduction method like dominant pole approximation is used to retain dominant dynamics of the system. Under this method, key poles with the strongest impact on the system behaviour are kept and the poles that have lesser impact to the system are ignored.

Putting the leading poles s=-1, s=-2, the reduced second-order denominator will be of the form:

$$(s + 1)(s + 2) = s^2 + 3s + 2$$

In that way, the pruned-order transfer function can be as follows:

$$G_r(s) = \frac{2s + 5}{s^2 + 3s + 2}$$

This is a simplified version of the behaviour of the original system but with the computational complexity less(M. Jabari and A. Rad, 2025). System analysis and simulation is made easier as the order of the system is simplified four to two.

4.3 Performance Comparison

The accuracy of reduced-order model is compared between the dynamic behaviour of the reduced and the original system. Key performance indicators that are compared are the aspects of stability, transient response as well as approximation.

The difference between the actual and the reduced model response can be given as:

$$E(s) = |G(s) - G_r(s)|$$

When the error is smaller, it means that the reduced model is a close approximation of the behaviour of the original system. System response analysis reveals that the reduced-order system is stable and retains the major dynamic properties of the original system. Whilst there might be some minor adjustments in behaviour at higher frequency, the system response is sufficiently accurate to provide a real understanding of a control system functioning practically.

The findings indicate that model order reduction provides a high degree of reduction of system representation without degrading their performance(Ł. Łachand D. Svyetlichnyy, 2025). Reduced-order models thus offer an effective substitute to the analysis of complex control systems in particular in cases where computation efficiency and real time code execution are of significant value.

5. DISCUSSION

The findings reveal that model order reduction is a useful tool in reducing high-order models of control systems preserving the key system behaviour. The fourth-order transfer function was reduced to a second-order model, which resulted in a high reduction of system complexity and the stability was not at risk. The dominating pole representation technique was able to maintain the key dynamic traits of the original system. It means that the most important role in determining system response belongs to dominating poles, and the other poles have comparatively insignificant presence.

It can be seen that the transient behaviour and general stability of the original model can be achieved by the reduced system, as can be seen in the comparison made between the original and reduced models. Even though some deviations may be present in the higher frequency responses, the reduced-order model still gives a reasonable approximation to most realistic control system analyses(J. Berberich and F. Allgöwer, 2025). This observation is in line with other studies which postulates that reduced models have the ability to enhance the computational efficiency without compromising significant dynamic properties.

Also, when reduced computational demands in a controller design and simulation are required, simplified models are especially useful. Nevertheless, it is also noted in the study that it is imperative to choose relevant reduction techniques. Poor choice of pole or over reduction can result in the loss of considerable system dynamics(S. Masri et al., 2025). So, close consideration of the reduction methods should be given to make sure that the accuracy and stability of the system remain undamaged.

6. RECOMMENDATIONS AND CONCLUSIONS.

Conclusion

This paper discussed model order reduction as a concept and its application in control systems. High-order control system models are generally regarded to present true health of the system dynamics, but pose a challenge in analysis, simulated and the development of a controller, owing to their complexity. The results show that model order reduction methods are able to simplify the complex models of the system and preserve fundamental dynamic properties like the stability and transient response.This analysis demonstrated that by dominant pole approximation reducing an order fourth system to a second-order model, the dominant pole approximation did not affect the behaviour of the primary system at all and reduced the computational complexity enormously. The results generated by the reduced-order model were relatively close to the original system response, and this shows that the key poles play a major role in system dynamics. Generally, the research paper establishes that model order reduction is a useful technique of enhancing efficiency in control system study and execution without affecting the tolerability of system accuracy.

Recommendations

This study also suggests that the application of model order reduction methodologies should be taken into account when the design and analysis of complex control systems are developing, to enhance the level of computational efficiency. Proper general choice of reduction techniques needs to be ensured by engineers and researchers that needed to make sure that important time-dependent properties are maintained based on the nature of the system(F. Ding et al., 2025). Depending on the need and complexity of the system, techniques that can be used include balanced truncation, dominant pole approximation and moment matching. Also, the reduced models need to be

evaluated well by considering stability and response analysis to ensure that they are reliable before they can be implemented in practice.

Future Work

The use of higher order model order reduction methods in large scale and nonlinear control systems can be considered in future studies. More research can also be directed to compare the various reduction algorithms on simulation tools to quantify their level of accuracy in calculation. Moreover, the combination of model order reduction techniques with the present-day control design tools may offer some more efficient options to the engineering practice in the real time.

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