

Integrating Dynamic Systems, Vibration, and Control

Colonel Wayne E. Whiteman, Ph.D., P.E., Major Blace C. Albert
Department of Civil and Mechanical Engineering
United States Military Academy
West Point, NY 10996

Abstract

Undergraduate mechanical engineering curricula often provide Dynamic Systems, Control System Theory, and Vibration as separate course offerings. Students and faculty tend to compartmentalize these subjects. The approach toward teaching these subjects is also often separated and aggravates the problem of compartmentalization. This paper presents a proposed outline of an integrated two-semester course sequence in dynamic systems, vibration, and control at the junior or senior level of the undergraduate experience. Selected topics could also be arranged to provide a one-semester course. Prerequisites for this proposed offering include a basic knowledge of linear algebra and calculus through differential equations, statics, dynamics, mechanics of materials, and basic electrical circuit theory and analysis. A graphical overview, or mind map, of the course is provided along with a detailed description of the various topics covered and the sequencing of the material.

Introduction

This paper addresses the need for integrating topics within the mechanical engineering discipline. Specifically, the topics of system dynamics, vibrations, and controls should be integrated. These topics are often treated as separate course offerings in traditional undergraduate mechanical engineering programs. Textbooks are often separated along these disciplinary lines as well. Teaching and learning engineering in this fashion causes students and faculty to compartmentalize subject material, which in turn stifles creative problem solving. By treating dynamic systems, vibration, and control system theory as distinct subjects, the problem of compartmentalizing engineering topics is aggravated.

One way to alleviate this problem, within the mechanical engineering discipline, is to combine system dynamics, vibrations, and controls. These three topics blend together well, and can therefore be included in an integrated sequence that uses a simple, common sense approach to presenting the material. A proposed outline for an integrated, two-semester course sequence in these areas is presented in this paper. The target audience of the course would be at the undergraduate junior or senior level. Selected topics, from the same prospectus, could be arranged to provide a one-semester course as well. In the sections that follow, the rationale of the need for this type of offering is presented, along with the course prospectus that provides a summary of the course topics. The necessary prerequisites are also discussed. In addition to this, a graphical overview, or mind map, is provided to give the reader a sense of the overall objectives of the potential course. This graphical overview illustrates how well the topics of dynamics, vibrations, and controls can be integrated.

Background and Rationale

In a book now out of print, *Vibration Control* (McGraw-Hill, 1958), John N. MacDuff and John R. Curreri integrated, to an extent, vibration topics, “concerned with controlling the dynamic deflection and stress in mechanical systems,”¹ with feedback and automatic control topics in one textbook. Since that time, the majority of textbooks deal primarily in one of two distinct disciplinary areas; (1) vibration theory and analysis, or (2) control systems theory and analysis, with little integration of the two topics.

Offering an integrated dynamics/vibrations/controls course has a distinct advantage over the current paradigm that they must be offered separately. It is very easy for students in undergraduate programs to think of mechanical engineering as having a dozen subcategories. To the average student, fluids, thermodynamics, and heat transfer are very different. It is not easy for students to think in terms of thermal sciences. Similarly, they consider dynamics, vibrations, and controls to be three more specialized areas of mechanical engineering. This inability to summarize, synthesize, and relate courses hinders their problem solving ability. As young engineers in industry, they must be able to draw upon all of their resources in order to solve problems. They must think beyond the compartmentalization of their academics in order to be successful. Problems must be approached more from a view of the governing laws of nature; conservation of mass, momentum, and energy for example.

There is evidence that supports the fact that students need integrated courses to help them understand the mechanical engineering discipline. First, academia has recognized the need for students to work on interdisciplinary teams. The increase in the number of multidisciplinary projects at universities has grown considerably in the past 10-15 years in order to better train students for life as a practicing engineer. Why then should not the curriculum conform to support this? Second, the trend of integrated curricula has already begun in other areas. Thermal sciences, for example, is already heading in this direction. This is evidenced by the advent of new texts such as Çengel and Turner’s *Fundamentals of Thermal-Fluid Sciences*² or Moran, Dewitt, Shapiro, and Munson’s *Introduction to Thermal Systems Engineering: Thermodynamics, Fluid Mechanics, and Heat Transfer*³. This is a good trend, as it encourages students to think from a more global perspective, thus making them more creative and efficient problem solvers.

The topics of dynamics, vibrations, and controls could also be easily integrated. This idea has not been fully developed however. A literature search of the currently available textbooks does reveal some attempts to integrate vibration and control theory. *Introduction to Dynamics and Control*, by Leonard Meirovitch⁴ is more general, and more introductory, than the text envisioned in this paper. While Meirovitch’s approach is somewhat similar, the proposed offering in this paper would include more vibration applications and much more control theory in the areas of the root locus method, frequency response techniques, and an introduction to state-space control. William J. Palm III also offers a more integrated approach than most textbooks in his book, *Modeling, Analysis, and Control of Dynamic Systems*,⁵ but not to the extent envisioned in this paper.

As mentioned in the introduction, the course proposed in this paper could be a two-term offering, or a one-semester course if selected chapters are used. The prerequisites for the course would be

a basic knowledge of linear algebra and calculus through differential equations, statics, dynamics, mechanics of materials, and basic electrical circuit theory and analysis.

Mind Map

The majority of current textbooks in the area of vibration theory and analysis often deal with passive control of mechanical systems, through techniques such as vibration isolation, damping, vibration absorbers, etc. Rarely do these texts also include active control techniques and feedback. The course proposed in this paper would integrate and address both passive and active control.

Most vibration texts take advantage of the fact that the dynamic systems they are analyzing can be modeled mathematically with higher-order, linear, homogeneous equations. These equations have solutions of an exponential form. When these same systems are subject to external forces, the non-homogeneous equations are usually solved with the traditional method of undetermined coefficients. While most control theory textbooks work almost exclusively with Laplace transformations, vibration theory treatment of the Laplace domain is often cursory. In the course layout proposed in this paper, both time domain and Laplace domain solution techniques would be employed to show the student how these approaches relate to each other.

Figure 1 shows a mind map of the integrated treatment of dynamic systems, vibration, and control. Actual systems are physically modeled with ideal elements, and subject to various inputs. The response of the actual system can be compared to the response predicted by the mathematical model. Tests and comparisons of the results can be used to update the model if necessary, to better predict behavior and to aid in proper design. When active control of the response solution is desired, root locus, frequency response, or state-space techniques can be used to implement a compensator controller and meet design objectives, of a desired transient response, a reduction in steady-state error, and stability.

DYNAMIC SYSTEMS, VIBRATION, AND CONTROL

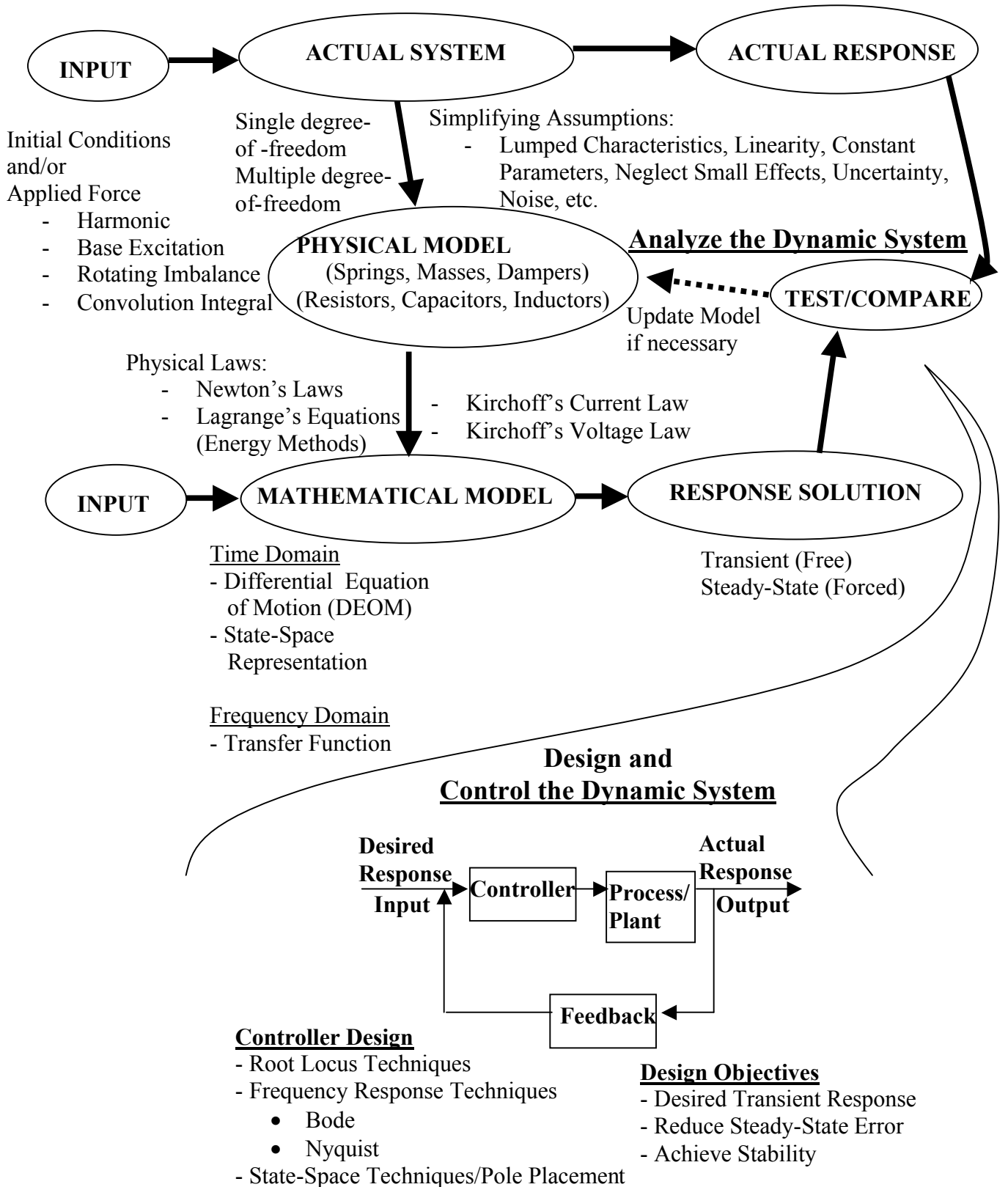


Figure 1. Course Mind Map

Prospectus

Table 1 shows a detailed prospectus of the proposed integrated course offering. By integrating what is normally treated as two distinct disciplines, some traditional topics have been omitted from the combined offering to allow the material to be completely covered in a two-semester sequence. Some of the topics from a traditional vibration course that are not covered in this integrated course are approximate solution methods, to include Rayleigh's Quotient and the Rayleigh-Ritz Method. Normal modes and modal analysis are also omitted, along with the vibration of continuous systems. The coverage is limited to rigid body dynamics, and nonlinear dynamics is not included. Only viscous damping is covered; there is no treatment of structural or coulomb damping.

When compared to a traditional control system offering, this proposed integrated course only models mechanical, electrical, and electromechanical systems. The modeling of hydraulic, thermal, and other types of systems is not covered. If these topics were deemed to be critical to the specific student's undergraduate program, they could easily be offered in an advanced elective in vibration and control. On the other hand, traditional controls courses often focus solely on classical control techniques, whereas graduate work teaches primarily modern state-space techniques. The integrated course proposed here would devote several lessons to the introduction of state-space control techniques. This would help to bridge the gap between students' undergraduate and graduate controls experience.

Table 1. Course Prospectus

Dynamic Systems, Vibration, and Control

Chapter 1 – Introduction

- 1.1 – Background of dynamic systems, vibration, and control
- 1.2 – Applications for dynamic systems, vibration, and control
- 1.3 – Analysis, design, and control objectives

Chapter 2 – Modeling Assumptions and Elements

- 2.1 – Simplifying assumptions
- 2.2 – Mechanical modeling elements
- 2.3 – Equivalent springs
- 2.4 – Electrical modeling elements

Chapter 3 – Modeling Mechanical Systems

- 3.1 – Modeling translational and rotational mechanical systems
- 3.2 – Modeling in the time domain: Newton-Euler formulation
- 3.3 – Modeling in the time domain: Energy-based formulation
- 3.4 – Time Domain: State-space representation
- 3.5 – Modeling in the frequency domain: Laplace transformations
- 3.6 – Modeling in the frequency domain: Transfer function representation
- 3.7 – Modeling mechanical gears

Chapter 4 – Modeling Electrical and Electromechanical Systems

- 4.1 – Modeling electrical systems
- 4.2 – Modeling in the time domain: Mesh analysis - Kirchoff's voltage law
- 4.3 – Modeling in the time domain: Nodal analysis - Kirchoff's current law
- 4.4 – Time domain: State-space representation
- 4.5 – Modeling in the frequency domain: Transfer function representation
- 4.6 – Modeling electromechanical systems in the time domain
- 4.7 – Modeling electromechanical systems in the frequency domain

Chapter 5 – Linearization and Conversions between the Time and Frequency Domain

- 5.1 – Linearization of equations
- 5.2 – Converting from a transfer function to state-space representation
- 5.3 – Converting from state-space Representation to a transfer function

Chapter 6 – Response Solution: First- and Second-Order Systems

- 6.1 – Response solution: First-Order systems
- 6.2 – First-Order systems: Time domain solution
- 6.3 – First-Order systems: Frequency domain solution
- 6.4 – Second-Order systems: Undamped transient time domain solution
- 6.5 – Second-Order systems: Damped transient domain solution
- 6.6 – Logarithmic decrement
- 6.7 – Second-Order systems: Undamped steady-state time domain solution
- 6.8 – Second-Order systems: Damped steady-state time domain solution
- 6.9 – Second-Order systems: Total response solution in the time domain
- 6.10 – Second-Order systems: Frequency domain solution

Chapter 7 – Second-Order Systems - Applications

- 7.1 – Rotating imbalance
- 7.2 – Base excitation
- 7.3 – Force transmission and vibration isolation
- 7.4 – Non-harmonic excitations

Chapter 8 – Higher-Order Systems

- 8.1 – Modeling in the time domain: Newton-Euler formulation
- 8.2 – Modeling in the time domain: Energy-based formulation
- 8.3 – Higher-Order systems: Undamped transient time domain solution
- 8.4 – Higher-Order systems: Damped transient time domain solution
- 8.5 – Higher-Order systems: Undamped steady-state time domain solution
- 8.6 – Application: Vibration absorber
- 8.7 – Higher-Order systems: Damped steady-state time domain solution
- 8.8 – Higher-Order systems: Total response solution in the time domain
- 8.9 – Higher-Order systems: Frequency domain solution

Chapter 9 – Control Design Objectives

- 9.1 – Achieving a desired transient response

- 9.2 – Stability
- 9.3 – Steady-state error

Chapter 10 – Controller Design: Root Locus Technique

- 10.1 – Block diagrams
- 10.2 – Root locus tools
- 10.3 – Controller design with the root locus method

Chapter 11 – Controller Design: Frequency Response Technique

- 11.1 – Bode analysis
- 11.2 – Nyquist criterion
- 11.3 – Controller design using the frequency response technique

Chapter 12 – Controller Design: State-Space Techniques

- 12.1 – Pole placement technique
- 12.2 – Controllability
- 12.3 – Observer design
- 12.4 – Observability

Conclusions

In this paper, an integrated course of dynamic systems, vibration, and control is presented. The course integrates conventional vibration theory and analysis as well as control theory and analysis offerings into a single treatment at the junior or senior undergraduate level. Integrating these topics would be very advantageous to students in mechanical engineering. Student perspectives of this change can be collected as part of future and ongoing course assessment. Annual assessments will provide student feedback regarding the ease of learning with the integration, and the ability to apply these topics to follow-on course work and senior design projects. Specific questions should be asked regarding the achievement of course objectives, whether the course processes are appropriate, and how well does the course objectives contribute to overall Program Educational Objectives.

Instead of compartmentalizing their learning, students exposed to the integration of topics described in this paper will better learn to think from a global perspective. This fosters creativity and confidence when solving problems. A course of this nature will also do a better job of preparing students to work as part of a multidisciplinary team, which is critical for their success as young engineers in industry. Current trends of integration can already be seen developing within mechanical engineering. Combining system dynamics, vibrations, and controls is the next logical step in the evolution of the mechanical engineering discipline.

References

- ¹ MacDuff, John N., and John R. Curreri, *Vibration Control*, McGraw-Hill Book Company, New York, 1958.

² Çengel, Yunus A., and Robert H. Turner, *Fundamentals of Thermal-Fluid Sciences*, McGraw-Hill, New York, 2001.

³ Moran, Michael J., et. al. *Introduction to Thermal Systems Engineering: Thermodynamics, Fluid Mechanics, and Heat Transfer*, John Wiley & Sons, 2002.

⁴ Meirovitch, Leonard, *Introduction to Dynamics and Control*, John Wiley & Sons, Inc., New York, 1985.

⁵ Palm, William J., *Modeling, Analysis, and Control of Dynamic Systems*, 2nd Ed., John Wiley & Sons, Inc., New York, 2000.

Biography

WAYNE E. WHITEMAN

Colonel Wayne E. Whiteman is an Associate Professor in the Department of Civil and Mechanical Engineering at the United States Military Academy, West Point. He received his BS from the United States Military Academy in 1979, an MSCE and Civil Engineer degree from MIT in 1987, and a Ph.D. in Mechanical Engineering from Georgia Tech in 1996. Colonel Whiteman has had numerous assignments with in the U.S. Army during his more than 23 years of active duty service. He is a registered professional engineer in the Commonwealth of Virginia.

BLACE C. ALBERT

Major Blace C. Albert is an Assistant Professor in the Department of Civil and Mechanical Engineering at the United States Military Academy (USMA) where he has served for three years. He graduated from USMA in 1991 with a B.S. in Mechanical Engineering (Aero) and received a Master of Science Degree in Mechanical Engineering from the Georgia Institute of Technology in 2000. He has served in the United States Army for twelve years.

Wei Wang, Mu Niu, Yuling Song, "Integrated Vibration Control of In-Wheel Motor-Suspensions Coupling System via Dynamics Parameter Optimization", *Shock and Vibration*, vol. 2019, Article ID 3702919, 14 pages, 2019. <https://doi.org/10.1155/2019/3702919>. Show citation. Integrated Vibration Control of In-Wheel Motor-Suspensions Coupling System via Dynamics Parameter Optimization. Wei Wang, Mu Niu, and Yuling Song 1,2,3. 1College of Mechanical and Electronic Engineering, Northwest A&F University, Yangling, Shaanxi 712100, China. The Integrated Dynamics Engineering (IDE) Group is a worldwide leader in developing and manufacturing environmental controls for active and passive vibration isolation, EMI active compensation, and acoustic isolation for research, metrology, lithography and medical systems; plus precision motion controls and robots for wafer and mask handling, tool platforms and EFEMs for semiconductor OEMs. Starting with unique active and passive vibration isolation systems, IDE expanded its product array to include a range of solutions for the most demanding industries in the instrumentation and metrology field. Integrated vehicle dynamics control system is an advanced system that coordinates all the chassis control systems and components to improve the overall vehicle performance including safety, comfort, and economy. Integrated vehicle dynamics control has been an important research topic in the area of vehicle dynamics and control over the past two decades. The research topic on integrated vehicle dynamics control is investigated comprehensively and intensively in the book through both theoretical analysis and experimental study. The paper introduces the flexible dynamics method in the trailer wheelset vibration performance and dynamic stress research. The flexible model of Undergraduate mechanical engineering curricula often provide Dynamic Systems, Control System Theory, and Vibration as separate course offerings. Students and faculty tend to compartmentalize these subjects. The approach toward teaching these subjects is also often separated and aggravates the problem of compartmentalization. Specifically, the topics of system dynamics, vibrations, and controls should be integrated. These topics are often treated as separate course offerings in traditional undergraduate mechanical engineering programs. Textbooks are often separated along these disciplinary lines as well. Teaching and learning engineering in this fashion causes students and faculty to compartmentalize subject material, which in turn stifles creative problem solving. INTEGRATED SYSTEMS. Vibration monitoring Complex monitoring Dynamic balancing Automated diagnostics. Authenticity safety reliability. 2. SPE & Vibrobit LLC core business is development and manufacture of Condition and Vibration Monitoring Systems (CVMS), information-technology (IT) systems, intended for mechanical status parameters continuous fixed measurement and monitoring of steam and gas turbines, turbocompressors, centrifugal pumps and other machines during their operation.