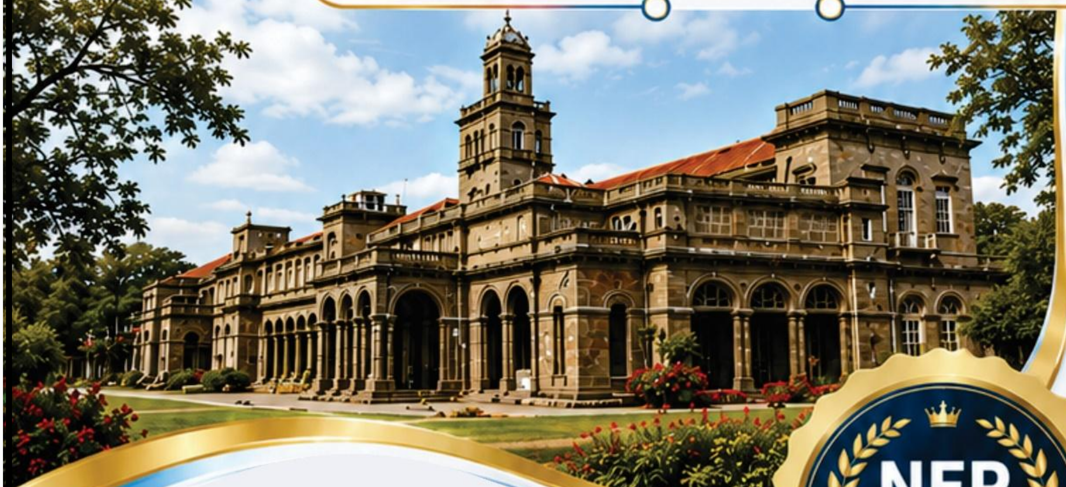
Savitribai Phule Pune University, Pune.

Maharashtra, India

Faculty of Science and Technology

Board of Studies (BoS)
Mechanical and Automobile Engineering



VEHICLE SUBSYSTEM ENGINEERING

POWERTRAIN SYSTEM

SUSPENSION & STEERING SYSTEM

BRAKING SYSTEM

ELECTRICAL & ELECTRONICS SYSTEM

HVAC SYSTEM

BODY STRUCTURE & SAFETY SYSTEM

NEP 2020

Honors Program in
VEHICLE SUBSYSTEM ENGINEERING
(20 Credits)

2024 PATTERN
(w.e.f. Academic Year: 2026-27)

Website: https://www.unipune.ac.in/

Contents

Semester: V, VI, VII & VIII Courses (Vehicle Subsystem Engineering)

NOMENCLATURE

AEC	Ability Enhancement Courses
AICTE	All India Council for Technical Education
CO	Course Outcome
CEP	Community Engagement Project
CCE	Comprehensive Continuous Evaluation
HSSM	Humanities, Social Science, and Management
MDM	Multidisciplinary Minor
MEC	Mechanical Engineering
MOOC	Massive Open Online Course
NPTEL	National Programme on Technology Enhanced Learning
NEP	National Education Policy
PCC	Program Core Course
PEO	Program Educational Objectives
PSO	Program Specific Objectives
SWAYAM	Study Webs of Active-learning for Young Aspiring Minds
UGC	University Grants Commission
VEC	Value Education Course
VSE	Vocational and Skill Enhancement Course
WK	Knowledge and Attitude Profile

PREFACE BY BOARD OF STUDIES

Dear Students and Teachers,

We, the members of the Board of Studies – Mechanical Engineering, are very happy to present the Third-Year Mechanical Engineering syllabus, effective from the **Academic Year 2026–27 (2024 Pattern).** We are confident that you will find this syllabus both interesting and challenging. The present curriculum will be implemented for Third Year Engineering from the academic year 2026–27, and it will be subsequently extended to the Final Years in the academic years **2027–28**.

Mechanical Engineering is one of the most sought-after branches among engineering students, which necessitates continuous revision and up gradation of the syllabus. Mechanical Engineering is a dynamic discipline that integrates principles from core engineering fields and supports innovation across manufacturing, design, energy, materials, and automation. This curriculum is designed to provide students with a comprehensive understanding of the fundamentals, emerging technologies, and practical applications in Mechanical Engineering, while also equipping them to meet the demands of a rapidly evolving industry.

The revised syllabus aligns with the vision of **NEP-2020**, and conforms to the frameworks set by Savitribai Phule Pune University, AICTE New Delhi, UGC, and various accreditation agencies. It takes into account recent technological developments, innovations, and industry needs to ensure students are well- prepared for professional challenges.

Wherever applicable, additional learning resources such as NPTEL and SWAYAM links are provided at the end of each course. Students are encouraged to utilize these platforms for self-learning, engage in online courses, and undertake additional projects to enhance their knowledge and skill set. On successful completion, they are advised to submit their course certifications, which will further support and enrich their academic growth.

This curriculum is the result of collaborative efforts involving academic experts, industry professionals, and alumni to ensure relevance and excellence. It is designed not only to meet current industry expectations but also to prepare students for higher studies, research, and entrepreneurial ventures in the field of Mechanical Engineering.

We hope this curriculum inspires students to become technically competent professionals, responsible citizens, and contributors to the technological and sustainable advancement of society.

Dr. Pradeep A. Patil
Chairman

PROGRAM SPECIFIC OUTCOMES

PSO1 : **SPECIFY, DESIGN** and **EVALUATE** mechanical components and systems using modelling and analysis software.

PSO2 : **APPLY** knowledge of machines, tools, automation, properties of advanced materials and modern management methods for manufacturing of mechanical components and systems.

PSO3 : **APPLY** core aspects of thermal and fluid engineering to determine the performance of mechanical systems including power absorbing and power generating systems.

PROGRAM EDUCATIONAL OBJECTIVES

Program Educational Objectives (PEOs) are broad statements that describe the career and professional accomplishments that the program is preparing a graduate to achieve.

PEO1 : The graduate will have a successful career in mechanical engineering with strong technical, research & professional skills.

PEO2 : The graduate will possess an ability to work in diversified fields along with team work and leadership qualities.

PEO3 : The graduate will continue to learn and to adapt in a society of constantly evolving technological environment

PROGRAM OUTCOMES

Program Outcomes (POs) are statements that articulate what students are expected to know, understand, and be able to do by the time they graduate from the program. These outcomes are aligned with the overall educational objectives of the program and reflect the skills, knowledge, attitudes, and behaviors acquired by students throughout their academic journey. On successful completion of B.E. in Mechanical Engineering, graduating students/graduates will be able to:

PO No.	Title	Program Outcome Description
PO1	Engineering Knowledge	Apply knowledge of mathematics, natural science, computing, engineering fundamentals and an engineering specialization as specified in WK1 to WK4 respectively to develop the solution of complex engineering problems.
PO2	Problem Analysis	Identify, formulate, review research literature and analyze complex engineering problems reaching substantiated conclusions with consideration for sustainable development. (WK1 to WK4)
PO3	Design / Development of Solutions	Design creative solutions for complex engineering problems and design/develop systems/components/processes to meet identified needs with consideration for public health and safety, whole-life cost, net zero carbon, culture, society and environment. (WK5)
PO4	Conduct Investigations of Complex Problems	Conduct investigations of complex engineering problems using research- based knowledge including design of experiments, modelling, analysis & interpretation of data to provide valid conclusions. (WK8)
PO5	Engineering Tool Usage	Create, select and apply appropriate techniques, resources and modern engineering & IT tools, including prediction and modelling, recognizing their limitations to solve complex engineering problems. (WK2 and WK6)
PO6	The Engineer and The World	Analyze and evaluate societal and environmental aspects while solving complex engineering problems for its impact on sustainability with reference to economy, health, safety, legal framework, culture and environment. (WK1, WK5, and WK7)
PO7	Ethics	Apply ethical principles and commit to professional ethics, human values, diversity and inclusion; adhere to national & international laws. (WK9)
PO8	Individual and Collaborative Team Work	Function effectively as an individual, and as a member or leader in diverse/multi-disciplinary teams.
PO9	Communication	Communicate effectively and inclusively within the engineering community and society at large, such as being able to comprehend and write effective reports and design documentation, make effective presentations considering cultural, language, and learning differences.
PO10	Project Management and Finance	Apply knowledge and understanding of engineering management principles and economic decision-making and apply these to one's own work, as a member and leader in a team, and to manage projects in multidisciplinary environments.
PO11	Life-Long Learning	Recognize the need for, and have the preparation and ability for: (i) independent and life-long learning, (ii) adaptability to new and emerging technologies, and (iii) critical thinking in the broadest context of technological change. (WK8)

KNOWLEDGE AND ATTITUDE PROFILE (WK)

WK No.	Focus Area	Description
WK1	Natural Sciences and Social Sciences	A systematic, theory-based understanding of the natural sciences applicable to the discipline and awareness of relevant social sciences.
WK2	Mathematics and Data Analysis	Conceptually-based mathematics, numerical analysis, data analysis, statistics and formal aspects of computer and information science to support detailed analysis and modelling applicable to the discipline.
WK3	Engineering Fundamentals	A systematic, theory-based formulation of engineering fundamentals required in the engineering discipline.
WK4	Engineering Specialist Knowledge	Engineering specialist knowledge that provides theoretical frameworks and bodies of knowledge for the accepted practice areas in the engineering discipline; much is at the forefront of the discipline.
WK5	Engineering Design and Environmental Considerations	Knowledge, including efficient resource use, environmental impacts, whole- life cost, re-use of resources, net zero carbon, and similar concepts, that supports engineering design and operations in a practice area.
WK6	Engineering Practice (Technology)	Knowledge of engineering practice (technology) in the practice areas in the engineering discipline.
WK7	Role of Engineering in Society	Knowledge of the role of engineering in society and identified issues in engineering practice in the discipline, such as the professional responsibility of an engineer to public safety and sustainable development.
WK8	Research and Critical Thinking	Engagement with selected knowledge in the current research literature of the discipline, awareness of the power of critical thinking and creative approaches to evaluate emerging issues.
WK9	Ethics and Inclusive Behavior	Ethics, inclusive behavior and conduct. Knowledge of professional ethics, responsibilities, and norms of engineering practice. Awareness of the need for diversity by reason of ethnicity, gender, age, physical ability, etc., with mutual respect.

Reference: Self-Assessment Report (SAR) Format Undergraduate Engineering Programs Graduate Attributes and Professional Competencies Version 4.0 (GAPC V4.0) - (August 2024) Page 55-56

GENERAL RULES AND GUIDELINES

Term	Definition
Course Outcomes (COs)	Course Outcomes are narrower statements that describe what students are expected to know and be able to do at the end of each course. These relate to the skills, knowledge, and behavior that students acquire throughout the course.
Assessment	Assessment is one or more processes, carried out by the institution, that identify, collect, and prepare data to evaluate the achievement of **Program Educational Objectives (PEOs)** and **Program Outcomes (POs)**.
Evaluation	Evaluation is one or more processes, performed by the **Evaluation Team**, to interpret the data and evidence gathered through assessment practices. It determines how well PEOs or POs are being achieved, and informs decisions for improvement.

ASSESSMENT AND EVALUATION:

Assessment and Evaluation shall be conducted in two parts:
1. Comprehensive Continuous Evaluation (CCE)
2. End-Semester Examination (ESE)

Component	Description	Marks
Comprehensive Continuous Evaluation (CCE)	Conducted at institute level, covering all Units of the syllabus. The design and mark allocation follow the Continuous Assessment Sheet structure.	**30**
End-Semester Examination (ESE)	Conducted at university level, typically covering the entire syllabus through summative examination.	**70**
	Total Marks per Subject	**100**

A) Comprehensive Continuous Evaluation (CCE) :

CCE to be conducted either on the basis of Mode 1 or Mode 2.

CCE MODE 1:

To design a Comprehensive Continuous Evaluation (CCE) scheme for a theory subject of 15 or 30 marks with the specified parameters, the allocation of marks and the structure can be as per continuous assessment sheet;

Savitribai Phule Pune University

Board of Studies (Mechanical and Automobile Engineering)

Comprehensive Continous Evaluation (CCE) [30 Marks Distribution]

Class: TE- Mechanical Engineering — Subject: Refrigeration and Air Conditioning

Exam Seat No.	Roll No.	Name of Student	Unit 1		Unit 2		Unit 3		Unit 4		Unit 5		Cumulative Sum				30 Marks Distribution				Marks obtained out
			Field Activity	Quiz	Field Activity	Quiz	Field Activity	Quiz	Field Activity	Quiz	Field Activity	Quiz	Field Activity	Quiz	Internal Test	Attendance	Field Activity	Quiz	Internal Test	Attendance	
			A	B	C	D	E	F	G	H	I	J	SUM(A+C+E+G+I)	SUM(B+D+F+H+J)			P	Q	R	S	SUM(P:S)
			10	10	10	10	10	10	10	10	10	10	50	50	100	100	15	5	5	5	30
T9028246474	2020	MAAN PANCHAL	8	8	8	8	8	8	8	8	8	8	40	40	60	75	12	4	3	3.8	22.75

Figure 1 Template Comprehensive Continuous Evaluation (CCE) *Click here to download* .**Field Activities / Home**

Assignments

Field activities and home assignments are essential components of experiential learning. Under this head, course projects, industrial visits, and guest lectures are to be incorporated. For each unit, one such activity should be designed and executed to reinforce theoretical learning through practical exposure.

1. **Course Projects**

   Course Projects should be framed based on real-world problems relevant to the subject. Each course project must be communicated through one of the following modes. It is recommended to complete all the communication modes across different course projects:

- **Poster Presentation**
- **PowerPoint Presentation**
- **Model Making**
- **Field or Survey Report with Oral Presentation** (e.g., case study)
- **Submission of Digital Content (e.g. Video Summary)**

To evaluate these field activities, **assessment rubrics** should be designed. The rubrics should include criteria such as clarity, innovation, subject relevance, presentation skills, and technical content.

Note: Part of work of any co-curricular activities (relevant to subject contents) like national level project competitions, club activities, paper presentations, startup activities can be accepted as a course projects.

2. **Industrial Visit**

   An industrial visit should be planned in alignment with the subject's scope and should particularly address advancements in the respective field. The purpose is to provide students exposure to actual engineering practices and systems.

   Assessment of industrial visits should be carried out using any of the following tools:

- Quiz (based on the visit)
- Interactive video or oral discussion
- Submission of a detailed visit report

3. **Guest Lectures**

   Guest lectures should be relevant to the course and highlight advanced topics or recent trends in the field. Subject experts from academia or industry may be invited.

   Assessment methods for guest lectures may include:

- Quiz conducted post-lecture
- Attendance monitoring
- Evaluation of attentiveness and participation

Rubrics can be developed, if possible, to objectively assess student involvement in guest lectures.

4. **Quiz**

   Unit-wise quizzes should be planned and can be conducted either **online** (Via LMS, Google Forms) or offline. Each quiz should include a **pool of 20 questions**, from which **students are required to attempt any 10**.

The quizzes should be diversified across the following question types:

- Simple Multiple Choice Questions (MCQs)
- Numerical MCQs
- Image-based Questions
- Match the Following
- Fill in the Blanks
- Drag and Drop (using images or words)

This variety ensures the assessment caters to different cognitive skills and learning styles.

5. Internal Tests

Two major internal tests should be conducted as follows:

1. **Midterm Examination**: This should cover **Unit I and Unit II**, and should include questions targeting **Bloom's Taxonomy Levels 2, 3, and 4** (UNDERSTAND, APPLY, and ANALYZE).
2. **End term Examination**: This should cover the **remaining units** and should also include questions mapped to **BL Levels 2, 3, and 4**.

CCE MODE 2:

Comprehensive Continuous Evaluation scheme in this mode for a theory subject of **30 marks** with the specified parameters, the allocation of marks and the structure can be detailed as follows:

Sr. No.	Parameters	Marks	Coverage of Units
1	Unit Test	12 Marks	Unit 1 & Unit 2 (6 Marks/Unit)
2	Assignments/Case Study	12 Marks	Unit 3 & Unit 4 (6 Marks/Unit)
3	Seminar Presentation/ Open Book Test/ Quiz	06 Marks	Unit 5

- **Unit Test–**

  Format: Questions designed as per Bloom's Taxonomy guidelines to assess various cognitive levels (Remember, Understand, Apply, Analyze, Evaluate, and Create).

  Implementation: Schedule the test after completing Units 1 and 2. Ensure the question paper is balanced and covers key concepts and applications.

- **Sample Question Distribution**–
  1. Remembering (2 Marks): Define key terms related to [Topic from Units 1 and 2].
  2. Understanding (2 Marks): Explain the principle of [Concept] in [Context].
  3. Applying (2 Marks): Demonstrate how [Concept] can be used in [Scenario]
  4. Analyzing (3 Marks): Compare & contrast [Two related concepts] from Units 1 and 2
  5. Evaluating (3 Marks): Evaluate the effectiveness of [Theory/Model] in [Situation].

- **Assignments / Case Study:** Students should submit one assignment or one Case Study Report based on Unit 3 and one assignment or one Case Study Report based on Unit 4.

  – ***Format***: Problem-solving tasks, theoretical questions, practical exercises, or case studies that require in-depth analysis and application of concepts.

– ***Implementation:*** Distribute the assignments or case study after covering Units 3 and 4. Provide clear guidelines and a rubric for evaluation.

- **Seminar Presentation: –**

  Format: Oral presentation on a topic from Unit 5, followed by a Q&A session.

  Deliverables**:** Presentation slides, a summary report in 2 to 3 pages, and performance during the presentation

  Implementation: Schedule the seminar presentations towards the end of the course. Provide students with ample time to prepare and offer guidance on presentation skills.

- **Open Book Test: –**

  Format: Analytical and application-based questions to assess depth of understanding. – **Implementation**: Schedule the open book test towards the end of the course, ensuring it covers critical aspects of Unit 5

- **Quiz:** –

  Format: Quizzes can help your students practice existing knowledge while stimulating interest in learning about new topic in that course. You can set your quizzes to be completed individually or in small groups.

  Implementation**:** Online tools and software can be used create quiz. Each quiz is made up of a variety of question types including multiple choice, missing words, true or false etc

- **Example Timeline for conducting CCE: –**

  1. Weeks 1-4 : Cover Units 1 and 2
  2. Week 5 : Conduct Unit Test (12 marks)
  3. Weeks 6-8 : Cover Units 3 and 4
  4. Week 9 : Distribute and collect Assignments / Case Study (12 marks)
  5. Weeks 10-12 : Cover Unit 5
  6. Week 13 : Conduct Seminar Presentations or Open Book Test or Quiz (6 marks)

- **Evaluation and Feedback: –**

  1. **Unit Test:** Evaluate promptly and provide constructive feedback on strengths and areas for improvement.
  2. **Assignments / Case Study:** Assess the quality of submissions based on the provided rubric. Offer feedback to help students understand their performance.
  3. **Seminar Presentation:** Evaluate based on content, delivery, and engagement during the Q&A session. Provide feedback on presentation skills and comprehension of the topic.
  4. **Open Book Test:** Evaluate based on the depth of analysis and application of concepts. Provide feedback on critical thinking and problem-solving skills.

B) End-Semester Examination (ESE)

Detailed Scheme for 60 Marks: Unit-Wise Allocation (12 Marks per Unit): Each unit will have a combination of questions designed to assess different cognitive levels. By following this scheme, you can ensure a comprehensive and fair assessment of students' understanding and application of the course material, adhering to Bloom's Taxonomy guidelines for cognitive skills evaluation.

Detailed Scheme for 40 Marks: Unit-Wise Allocation (08 Marks per Unit): Each unit will have a combination of questions designed to assess different cognitive levels. By following this scheme, you can ensure a comprehensive and fair assessment of students' understanding and application of the course material, adhering to Bloom's Taxonomy guidelines for cognitive skills evaluation The following structure is to be followed for designing an ESE for a **theory subject of 60 marks** covering **all 5 units** of the syllabus, with **questions set as per Bloom's Taxonomy** guidelines and **12 marks allocated per unit**.

2. Balanced Coverage

Ensure balanced coverage of all units with questions that assess different **cognitive levels of Bloom's Taxonomy**:

a) **Remembering**: Basic recall of facts and concepts.
b) **Understanding**: Explanation of ideas or concepts.
c) **Applying**: Use of information in new situations.
d) **Analyzing**: Drawing connections among ideas.
e) **Evaluating**: Justifying a decision or course of action.
f) **Creating**: Producing new or original work (if applicable).

Curriculum Structure
Honor Courses (2024 Pattern)
NEP 2020 Compliant Curriculum Structure

Savitribai Phule Pune University

Board of Studies - Mechanical and Automobile Engineering

Undergraduate Program – Third and Final Year Mechanical Engineering (2024 pattern)

Course Code	Course Type	Course Name	Teaching Scheme (Hrs./week)			Examination Scheme and Marks						Credits			
			L	T	P	CCE	ESE	TW	OR	PR	TOTAL	L	T	P	TOTAL
Semester-V															
HVSE301MEC	Honor Course	Fundamentals of Machine Design and Optimization	4			30	70				100	4			**5**
HVSE302MEC	Honor Course	Material Characterization and Optimization lab			2			25	25		50			1	
Semester-VI															
HVSE351MEC	Honor Course	Finite Element Analysis and Design of Experiments	3			30	70				100	3			**5**
HVSE352MEC	Honor Course	Simulations-based Design and Analysis Lab			4			25	25		50			2	
Semester-VII															
HVSE401MEC	Honor Course	Fundamentals of Low Frequency NVH and Automotive Applications	3			30	70				100	3			**5**
HVSE402MEC	Honor Course	Vehicle Vibration Analysis Lab			4			25	25		50			2	
Semester-VIII															
HVSE451MEC	Honor Course	Multibody Dynamics and Vehicle Dynamics	4			30	70				100	4			**5**
HVSE452MEC	Honor Course	Multibody Dynamics Simulation lab			2			25	25		50			1	
		Total	**14**		**12**	**120**	**280**	**100**	**100**		**600**	**14**		**06**	**20**

Savitribai Phule Pune University, Pune

Maharashtra, India

TE Mechanical Engineering
(2024 Pattern)

SEMESTER- V

Honor Courses

[Vehicle Subsystem Engineering]

<table>
<tr><td colspan="5">.
Savitribai Phule Pune University
Third Year of Mechanical Engineering (2024 Pattern)</td></tr>
<tr><td colspan="5">HVSE301MEC: Fundamentals of Machine Design and Optimization</td></tr>
<tr><td colspan="2">Teaching Scheme</td><td>Credit</td><td colspan="2">Examination Scheme</td></tr>
<tr><td>Theory</td><td>4 Hours/Week</td><td rowspan="2">4</td><td>CCE</td><td>30 Marks</td></tr>
<tr><td>Practical</td><td>NA</td><td>End-Semester</td><td>70 Marks</td></tr>
</table>

- **Prerequisites:** Engineering Mechanics, Solid Mechanics, Engineering Materials & Metallurgy, Material Testing and Characterization lab, Design of Machine Elements

Course Objectives:

After completing this course, students will be able to:

1. **ACQUIRE** knowledge of advanced engineering materials and global standards used for physical metallurgy in the automotive industry
2. **ACQUIRE** knowledge of analyzing 3D trusses and structures involving mechanisms, using free-body diagrams
3. **UNDERSTAD** formulation of optimization problems incorporating design and manufacturing constraints
4. **SOLVE** optimization problems using linear and nonlinear programming techniques
5. **INTERPRET** optimization results and understand the capabilities and limitations of optimization solvers

Course Outcomes: On completion of the course, students will be able to

CO1: MEASURE the physical and mechanical properties of materials in accordance with global testing standards and APPLY the resulting data to product design and development.

CO2: CALCULATE internal and reaction forces in 3D trusses and structures involving beams and axially loaded members

CO3: FORMULATE optimization problems for structural design and operations research applications

CO4: FORMULATE and solve engineering optimization and operation research problems using graphical, and linear programming & nonlinear programming methods

CO5: APPLY optimization principles to identify critical constraints, key design variables that influence the optimal solution, do what-if studies, and do trade-off analyses

Course Contents

Unit I	Engineering Materials and Measuring Physical Properties of Materials	09 Hours

Materials used in the automotive industry and its applications for improving strength, lightweighting, fatigue life, NVH etc. including cold rolled steel, hot rolled steel, advanced high-strength steel, aluminum alloys, magnesium, polymer composites, MMC, thermoset composites, ADI, and CGI, low, medium, and high carbon steels, tensile testing using ASTM E8 standard, strain control and displacement control test, identify the yield stress with 0.2% offset as per ASTM E8, Brinell hardness as per ASTM E10, and Vickers hardness & Knoop microhardness as per ASTM E92 & E384, applications of hardness testing in automotive industry, elastomer applications for vibration isolation, static & dynamic stiffness of elastomers, interpretation of hysteresis graphs to determine dynamic stiffness and phase angles, dynamic stiffness versus frequency characteristics of viscoelastic material, characterizing fatigue life and fatigue properties of materials-electrodynamic shakers, servo-hydraulic systems, and the rotating beam bending test, low and high cycle fatigue test, variability in fatigue life, design consideration for improving fatigue life, strain measurements using strain rosettes and converting test data to principal strains using Mohr's circle, derivation of true stress & true strain equations, converting engineering stress versus strain data to true stress versus strain data with examples, relationship between E, G, and ν.

Real World Assignments

1. Study fatigue testing procedures for front forks and shock absorbers, including low-cycle and high-cycle fatigue, and identify manufacturing processes that improve the fatigue life of fork pipes.
2. Determine principal strains and stresses from strain-rosette measurements and study their application in test–CAE correlation.
3. Study how Advanced High-Strength Steels (AHSS) enhance BIW crashworthiness while enabling weight reduction, with specific examples of their automotive applications and implementation.
4. Identify lightweight materials and manufacturing processes used in Body-in-White (BIW), with suitable automotive examples.

Exemplars / Practical Applications

1. Thermoset composites are used for manufacturing automotive body panels
2. Motorcycle headlamp design validation is performed using electrodynamic shakers
3. Elastomers are widely used for vibration isolation in automotive industry

Unit II	Analysis of 3D Trusses and 3D Structures with Beams & Pin Joint Structures	06 Hours

Real-world examples of statically determinate structures and indeterminate structures, moment of a force in 3D space, moment of a couple analyzed in 3D space, the resultant moment of multiple forces in 3D space, resultant force from a set of forces acting orthogonal to a plane in 3D space, the resultant of a set of moments in 3D space, 3D structural analysis of space trusses, frames, and machines like earth moving equipment containing internal hinges with combination of beams and axially loaded elements like actuators, draw free-body diagrams, axial force, shear force, and bending moment diagrams, calculate principal moments of inertia (3x3 matrix) and principal axes by solving the eigenvalue problem, understanding the orientation of the principal axes and principal moment of inertia & its applications.

Real World Assignments

1. Study various types of truss structures used in industrial sheds and identify the configurations and details of gusset plates used at the joints. Explain the design methodology for gusset plates subjected to different tensile and compressive axial forces.
2. Analyze an earth-moving machine to determine its maximum load-carrying capacity based on allowable stress limits. Model the individual structural members as beams, wherever appropriate, and represent axial load-carrying components such as hydraulic actuators using pin-jointed connections. Perform the analysis in a 2D plane, generate axial force, shear force, and bending moment diagrams, and determine the maximum safe load-carrying capacity.

Exemplars / Practical Applications

1. Space-frame structures are used for creating column-free spaces in airport terminals
2. Design and analysis of overhead cranes
3. Vibration analysis of an engine modeled as a rigid body with mass and principal moments of inertia and engine mounts

Unit III	Fundamentals of Optimization	10 Hours

Definition of local minima & maxima, global minima & maxima, finding the gradient and Hessian matrix of a function and its applications in identifying local extrema, steepest descent direction, Taylor series expansion of a function, stationary points, necessary and sufficient conditions for locating minima, maxima, and saddle points, optimization problem formulation including minimization or maximization of an objective function, equality & inequality constraints, unconstraint and constrained optimization, design variables and bounds, bounded vs unbounded problems, optimization problem formulation for structural problems and operation research.

Real World Assignment

1. Steering column frequency optimization: Formulate an optimization problem to maximize the natural frequency of a car steering column. Model the steering column as a cantilever beam with the steering wheel

and airbag represented as a concentrated mass at the free end. Assume appropriate design variables, manufacturing constraints, and geometric constraints.

2. Optimizing the cost of manufacturing a packaging box: Formulate an optimization problem to minimize the manufacturing cost of a box for a specific volume. Survey different box dimensions available for a fixed volume based on the data available in the public domain and determine the most optimal design based on the minimum surface area of the box.

Exemplars / Practical Applications

1. Minimize the cost or maximize the fatigue life of a two-wheeler
2. Maximize the fundamental natural frequency of an aircraft wing
3. Maximize the buckling strength of an electric pole

Unit IV	**Graphical Method and Linear Programming (LP)**	**12 Hours**

Optimization methods- optimality criteria and search techniques, constraint & unconstraint problems, graphical method applied to problems with two design variables explained through case studies such structural problem and operation search with two variables and inequality & inequality constraints, convex polyhedron representing the feasible solution space, active constraints, identification of feasible and infeasible regions, Linear Programming (LP) problem definition, cost function, constraints, design variables, converting inequality constraints into equality constraints, Simplex method, basic and non-basic variables, duality in linear programming, interpretation of Lagrange multipliers, sensitivity analysis, what-if studies & trade-off analysis, solving LP problems using numerical computing or optimization software, case studies of LP with applications to automotive & operation research problems.

Real World Assignment

1. Packaging cost optimization: For an oil manufacturing company, minimize packaging cost by maximizing the oil container volume, subject to constraints on the can dimensions and maximum allowable surface area.

2. MacPherson strut spring design optimization: Design a manufacturable and cost-effective spring for a MacPherson strut by optimizing the wire diameter, coil diameter, and number of coils to minimize spring weight while satisfying requirements for load capacity, deflection, stress, solid height, and natural frequency.

Exemplars / Practical Applications

1. Optimal allocation of machines to maximize overall profit
2. Selection of optimal warehouse locations to minimize transportation cost
3. Optimal allocation and utilization of a rental car fleet to maximize operational efficiency and profitability based on customer demand

Unit V	**Constraint and Unconstraint Nonlinear Optimization**	**11 Hours**

Unconstrained optimization- one-dimensional and multidimensional search methods, unconstraint optimization- steepest descent, conjugate gradient, and Newton's methods, step-size determination using the equal interval & golden-section search methods, introduction to gradient-based constrained optimization methods, constraint linearization using sensitivity analysis implemented in finite element solvers, sequential linear programming method for solving nonlinear problems, introduction to SQP and interior point methods.

Real World Assignment

1. Motorcycle handlebar optimization: Increase the first natural frequency of a motorcycle handlebar while minimizing its weight, subject to design and manufacturing constraints on tube outer diameter and wall thickness.

2. Motorcycle side-stand cost optimization: Reduce the cost and weight of a motorcycle side stand by studying and comparing different side-stand designs used in motorcycles, considering their structural performance, manufacturability, weight, and cost.

3. Scooter grab-handle cost optimization: Reduce the cost and weight of a rear-seat grab handle for a scooter by studying and comparing different grab-handle designs, evaluating their strength, weight, manufacturability, and cost. Make suitable assumptions for the loads and boundary conditions for performing the analysis using a beam model.

Exemplars / Practical Applications

1. Perform vibration reduction of a motorcycle frame using road loads
2. Reduce stresses in a motorcycle frame subjected to a pothole event
3. Improve the bending and torsional stiffness of a three-wheeler rickshaw body

Learning Resources

Text Books

1. Mechanical metallurgy, G.E. Dieter, McGraw-Hill Book Company
2. Engineering mechanics statics and dynamics, R.C. Hibbeler and Ashok Gupta, Pearson Prentice Hall
3. Mechanics of materials, J.M. Gere and S.P. Timoshenko, CBS Publisher & Distributors Pvt. Ltd.
4. Introduction to optimum design, J.S. Arora, McGraw Hill Book Company

Reference Books

1. Material science and metallurgy for engineers, V.D. Kodgire & SV. Kodgire, Everest Publishing House
2. Engineering optimization theory and practice, S.S. Rao, New Age International Publisher
3. ASTM standards - E8, E10, E23, E92, and E384, ASTM International
4. Schaum's outline, Vector Analysis, M.R. Speigel, S. Lipschutz, and D. Spellman, Tata McGraw Hill Education Private Limited
5. Schaum's outline series, Mathematical handbook, M.R. Spiegel, McGraw Hill Publishing Company
6. Thomas Calculus, M.D. Weir, J. Hass, and F.R. Giordano, Person
7. Noise and vibration control engineering- principles and applications, edited by L.L. Beranek and I.L. Ver, Wiley-Inter science, John Wiley & Sons, Inc.
8. Theory of elasticity, S.P. Timoshenko & H.B. Goodier, McGraw Hill Education (India) Private Limited

Web reference

1. Prof. Adrijit Goswami, NPTEL course- Constraint and Unconstraint Optimization
https://www.youtube.com/watch?v=gw_ZEUjI9KM&list=PLYihddLF- CgZGDFVwB1v699kvl4FMeAr-

Savitribai Phule Pune University
Third Year of Mechanical Engineering (2024 Pattern)

HVSE302MEC: Material Characterization and Optimization Lab

Teaching Scheme		Credit	Examination Scheme	
Theory	NA	1	TW	25 Marks
Practical	2 Hours/Week		OR	25 Marks

- **Prerequisite courses:** Engineering Mechanics, Solid Mechanics, Engineering Materials & Metallurgy, Material Testing and Characterization Lab, Design of Machine Elements, Fundamentals of Machine Design and Optimization

Course Objectives:

After completing this course, students will be able to:

1. **ACQUIRE** knowledge of ASTM material testing standards
2. **UNDERSTAND** the importance of sample preparation and standardized testing procedures as per ASTM standards
3. **LEARN** various material characterization techniques and their applications
4. **FORMULATE** and solve optimization problems using various software tools, and results interpretation
5. **APPLY** various optimization techniques for solving engineering and operations research problems

Course Outcomes:

After successful completion of the course, learner will be able to:

CO1: PERFORM material testing in accordance with ASTM testing standards and procedures

CO2: UTILIZE material test data in product design and development, including finite element simulations, and ensuring product quality during manufacturing

CO3: APPLY optimization techniques to engineering problems for weight and cost reduction and performance improvement, using Linear Programming (LP) and nonlinear programming (NLP) methods

CO4: UTILIZE software tools to solve complex optimization problems involving multiple design variables and constraints

CO5: DESIGN automotive components for weight reduction while satisfying design and manufacturing constraints, and PERFORM what-if studies and trade-off analyses

Guidelines for Conducting Laboratory Experiments

The student shall complete the following hands-on activities as a Term Work under the guidance of concerned faculty member. The open-source software shall be preferred for conducting practical sessions.

Course content

Following are the compulsory experiments

Experiment 1: Tensile Testing as per ASTM E8 Standard

Conduct a tensile test experiment with the extensometer and record the stress verses strain diagram for various materials with strain- or displacement- controlled test. Make a drawing of the test sample as per ASTM E8 standard and measure actual dimensions of the sample. Document and interpret the results. Study the failure surface of the test specimen and compare the same for different materials. Derive true stress versus strain diagram from the engineering stress versus strain diagram for steel and aluminum alloys. Measure the reduction in the diameter of the sample at the failure and calculate the true stress.

Exemplars / Practical Applications:

Material characterization of products such as alloy wheels and control arms to determine yield strength, ultimate tensile strength, and elongation using strain- and displacement-controlled tensile tests in accordance with ASTM E8 standards. This data is further used for getting true stress versus strain curve, which is used in nonlinear FE simulations.

Experiment 2: Hardness Testing as per ASTM E10, E92, and E384

Conduct Brinell hardness, Vickers hardness, or Knoop hardness test as per ASTM E10, E92, and ASTM E384 standards. Prepare the sample as per ASTM requirements. Prepare test samples from automotive components such as front fork pipes with Ni-Cr coating, heat treated Die steel, Aluminum alloy wheel, forged aluminum etc. and explain application of various hardness testing for different manufacturing processes and applications.

Exemplars / Practical Applications:

Process control for T6 heat treatment for alloy wheels and Ni-Cr coating processes for suspension components are implemented through hardness testing, in accordance with engineering drawing specifications. Hardness testing is also done to measure and control manufacturing process variability.

Experiment 3: Impact Testing as per ASTM E23

Perform an impact test using ASTM E23 with either Charpy or Izod impact and record & interpret the results for ferrous and nonferrous samples. Make the drawing of the test sample and measure the dimensions of the actual sample. Document the significance of impact strength in product design and development.

Exemplars / Practical Applications:

To ensure the required product quality and performance under impact loading, safety-critical components such as aluminum alloy wheels and bottom cases are evaluated through impact testing in accordance with ASTM E23 standards.

Experiment 4: Measuring Principal Strains with a DAQ & Strain Rosette

Conduct an experiment with a strain rosette, measure strains in 3 directions, and find out the principal strains and principal directions for a cantilever beam with a load at a tip. Document surface preparation, pasting the strain gages, and measuring strains using Data Acquisition System under given load conditions. Find out the principal strains using the strain rosette results, using hand calculations. Check if the strain gage readings indicate the anticlastic curvature for the cantilever beam, as per the beam theory.

Exemplars / Practical Applications:

Correlation between experimental test results and CAE predictions is essential for establishing confidence in simulation models and their application in design guidance. This is achieved by measuring principal strains using strain rosettes during testing and comparing the results with corresponding FEA predictions for 2-, 3-, and 4-wheeler component design and development.

Experiment 5: Solving Nonlinear Optimization Problem with a Numerical Computing Software

Formulate and solve the optimization problem using the graphical method and an NLP optimization solver using numerical computing software or optimization software for maximizing the buckling load of an axially loaded hollow circular column, with a fixed support at the base and a free boundary at the top. Assume the numerical values for the material, length of the column L, the outer diameter and the thickness of the tube. The first natural frequency of the column f_1 need to meet upper and lower bounds as-

$$f_{upper\ limit} \geq f_1 = \frac{(1\cdot 875)^2}{2\pi L^2}\sqrt{\frac{EI}{\rho A}} \geq f_{lower\ limit}$$

Define tube outer diameter and the thickness as design variables with the upper and lower limits. Ensure that the design problem has feasible design space by choosing the appropriate upper and lower bounds and the constraints. Solve the problem graphically and a numerical computing or optimization software r to identify the optimal design and perform post optimality analysis.

Exemplars / Practical Applications:

Real-world vehicle design problems often involve nonlinear objective functions and constraints. Therefore, nonlinear programming (NLP) solvers play an important role in the automotive design and development process.

Experiment 6: Manufacturing Cost Optimization Using Linear Programming and Numerical Computing or Optimization Software

Formulate and solve a manufacturing cost minimization problem using Linear Programming (LP) problem using numerical computing or optimization software. A cabinet is assembled from three components C1, C2, and C3. Each cabinet requires 8 number of C1 components, 5 number of C2 components, and 15 number of C3 components. Assembly of C1 needs 5 bolts or 5 rivets, C2 needs 6 bolts or 6 rivets, and C3 needs 3 bolts or 3 rivets. The labor and material cost of the bolt are Rs. 70 for C1, Rs. 100 for C2, and Rs 60 for C3. The labor and the material cost for the rivet are Rs. 60 for C1, Rs. 80 for C2, and Rs. 100 for C3. A total of 100 cabinets must be assembled daily. Bolting and riveting capacity are 7000 and 9000 per day, respectively. Determine the number of components to be bolted and riveted to minimize the cost. You can add more constraints as appropriate, ensuring a feasible design space. Find out the optimized solution, objective function, and constraint values. Interpret Lagrange Multiplier results and identify critical constraints. Interpret results, do what-if studies and trade-off analysis and verify the new optimal solution with reanalysis.

Exemplars / Practical Applications:

Optimizing transportation costs for an OEM to distribute vehicles among various dealerships based on customer demand is critical for efficient supply chain management. This is achieved by formulating and solving the problem using linear programming method.

Experiment 7: Implementation of Steepest Descent Method Using a Computing Software

Develop and implement a computer code to solve an unconstraint minimization program using steepest descent method and equal interval search & golden search methods. Formulate and solve a problem with the computer code to minimize a function. Alternatively, you can use a numerical computing or optimization software to formulate & solve the problem.

Exemplars / Practical Applications:

Noise and vibration problems are modeled using finite element techniques, while nonlinear optimization problems are linearized and solved using Sequential Linear Programming (SLP) techniques. Taylor's series approximations are used and are valid for solving automotive problems.

Guidelines for the term work

1. Term work consists of problem formulation, collecting relevant material data, assigning appropriate dimensions, and analyzing customer usage to establish loads & boundary conditions. The goal is to represent a real-world problem. A clearly defined problem statement is critical, as it ensures a meaningful formulation and leads to a valid solution.
2. Compulsory experiments must be presented with step-by-step procedures, supported by neat figures, free-body diagrams, detailed calculations, photographs as required, assumptions, results interpretation, and conclusions. The student's ability to define and solve problems should be assessed. Each experiment must include necessary references.

Learning Resources

Text Books

1. Mechanical metallurgy, G.E. Dieter, McGraw-Hill Book Company
2. Engineering mechanics statics and dynamics by R.C. Hibbeler and Ashok Gupta, Pearson Prentice Hall
3. Mechanics of materials, J.M. Gere and S.P. Timoshenko, CBS Publisher & Distributors Pvt. Ltd.
4. Introduction to optimum design, J.S. Arora, McGraw Hill Book Company

Reference Books

1. Material science and metallurgy for engineers, V.D. Kodgire & SV. Kodgire, Everest Publishing House
2. Engineering optimization theory and practice, S.S. Rao, New Age International Publisher
3. ASTM standards - E8, E10, E23, and E92, ASTM International
4. Schaum's outline, Vector Analysis, M.R. Speigel, S. Lipschutz, D. Spellman, Tata McGraw Hill Education Private Limited
5. Schaum's outline series, Mathematical handbook, M.R. Spiegel, McGraw Hill Publishing Company
6. Thomas Calculus, M.D. Weir, J. Hass, and F.R. Giordano, Person
7. Noise and vibration control engineering- principles and applications, Edited by L.L. Beranek and I.L. Ver, Wiley-Interscience, John Wiley & Sons, nc.
8. Theory of elasticity, S.P. Timoshenko & H.B. Goodier, McGraw Hill Education (India) Private Limited

Web References

1. Prof. S. Sankaran, IIT Madras, NPTEL course- Mechanical Behavior of Materials https://www.youtube.com/watch?v=s4TRNH4I9J0&list=PLyqSpQzTE6M9QPU_tubmtQ97e7zRpaMlD&index=1&t=37s

Savitribai Phule Pune University, Pune
Maharashtra, India

TE - Mechanical Engineering (2024 Pattern)

SEMESTER- VI

Honor Courses

[Vehicle Subsystem Engineering]

Savitribai Phule Pune University
Third Year of Mechanical Engineering (2024 Pattern)

HVSE351MEC: Finite Element Analysis and Design of Experiments

Teaching Scheme		Credit	Examination Scheme	
Theory	**3 Hours/Week**	**3**	**CCE**	**30 Marks**
Practical	**NA**		**End-Semester**	**70 Marks**

- **Prerequisite courses:**
  Solid Mechanics, Design of Machine Elements, Engineering Simulations and Analysis, Fundamentals of Machine Design and Optimization

Course Objectives:

After completing this course, students will be able to:

1. **LEARN** the formulation and solution of structural, thermal, and flow problems using direct & variational methods, with applications in automotive industry
2. **DEVELOP** practical skills in modelling real-world engineering systems with suitable elements, materials, loads, and boundary conditions
3. **LEARN** advanced modeling techniques using special elements and connectors to develop simplified finite element models that accurately represent real-world engineering problems
4. **INTERPRET** FEA results including stresses, strains, displacements, reaction forces, and temperature distributions, and evaluate the corresponding factors of safety
5. **INTRODUCE** Design of Experiments (DoE) method coupled with simulation-based analysis & optimization for engineering design improvement and informed decision-making

Course Outcomes:

After successful completion of the course, learner will be able to:

CO1: FORMULATE linear finite element problems for real-world structural and thermal automotive engineering applications

CO2: DERIVE shape functions, element stiffness matrices, force vectors, and equilibrium equations for 1D, 2D, and 3D elements

CO3: DEVELOP and ANALYZE FEA models using appropriate boundary conditions, constraints, couplings, joints, mesh controls, and consistent unit systems

CO4: EVALUATE structural and heat-transfer problems using analytical methods and commercial FEA software, and validate the numerical results against hand calculations

CO5: DESIGN and **ANALYZE** DoE studies to identify significant factors and interactions, determine optimum settings, and develop response-based optimized engineering solutions

Course Contents

Unit I	Introduction to Finite Element Analysis	07 Hours

Applications of FEA in the automotive industry for NVH, durability, crashworthiness, and manufacturing process simulations, understand the role of simulations into APQP process, integrating simulations into the multi-functional optimization, mesh quality controls and mechanism generation due to errors in FEA modeling, linear & nonlinear FEA, types of nonlinearities, assumptions of linear FEA, theory of elasticity-equilibrium conditions, boundary conditions, strain displacement & stress strain relationships, & compatibility conditions, plane stress & plane strain problems, review of matrix algebra including matrix operations, dot and cross products, essential and natural boundary conditions, numerical solution techniques for linear systems and eigenvalue problems, consistent unit systems, direct method for 1D spring & 1D bar, 2D truss, flow in pipe networks, & electrical networks, element & global stiffness matrix, boundary conditions, and load vector.

Real World Assignment

1. Develop and validate a finite element model of an automotive component by evaluating mesh quality parameters such as aspect ratio, Jacobian, warpage, and skewness, against industry-accepted guidelines. Define realistic boundary conditions and loading based on the component's service conditions, and perform mesh-refinement studies to establish solution convergence.
2. Perform structural and fatigue analysis of a motorcycle front fork to determine the stresses in the fork pipes under representative bending loads. Estimate the maximum service load generated during a real-world pothole event. Obtain an appropriate S–N curve for the fork-pipe material, and predict the fatigue life based on the FEA stress results.

Exemplars / Practical Applications

1. Perform automotive crashworthiness analysis of a vehicle using FEA to meet crashworthiness compliance requirements
2. Perform vehicle durability analysis using measured road-load data and FEA software
3. Perform die-casting process simulations to predict and minimize casting defects and optimize process parameters for achieving defect-free components
4. Perform sheet-metal stamping process simulations to identify optimal process control parameters and minimize defects for achieving defect-free stamped components

Unit II	Finite Element Formulation for 1D, 2D, and 3D Structural Problems	11 Hours

Identify the degrees of freedom, reaction forces, & resulting boundary conditions in 3D space for various supports including a cable, roller, ball and socket, & fixed support, variational method & Euler Lagrange equations from a functional, define degrees of freedom, derive shape functions, and element stiffness matrix for- 1D spring, 1D bar, 1D Euler-Bernoulli beam, and 2D truss, 2D frame, CST elements, and axisymmetric solid, natural coordinate system, Jacobian matrix, assembly for the global stiffness matrix, force vectors for various loading, case studies for the above elements using hand calculations and commercial finite element analysis software.

Real World Assignment

1. Perform static stress analysis and estimate fatigue life of an automotive alternator bracket using the dimensions, material properties, mounting conditions, and representative operational loads of a real-world alternator bracket.
2. Perform static structural stress analysis of an automotive engine mounting bracket by defining realistic material properties, constraints, and engine loading conditions, and evaluate the resulting stresses and deformations.
3. Perform static stress analysis of an automotive brake master cylinder using realistic geometry, material properties, constraints, and hydraulic loading conditions, and predict the resulting stresses and deformation.

Exemplars / Practical Applications

1. Estimate the fatigue life of a Body-in-White (BIW) under road load conditions and identify critical locations prone to fatigue failure
2. Evaluate the stresses and fatigue performance of an aluminum-alloy wheel subjected to representative cornering and torsional fatigue test loads
3. Determine the maximum load carrying capacity of a two-wheeler front fork bottom case by simulating a bend test

Unit III	Finite Element Formulation for 1D Steady-state Heat Transfer Problems	06 Hours

Heat transfer governing differential equation, steady-state formulation of 1D element for conduction and convection problem using variational method, boundary conditions, solution for heat transfer problem with numerical examples and with finite element analysis software.

Real World Assignment

1. Develop a 1D analytical and FEA model of an automotive brake disc to predict the steady-state temperature distribution due to frictional heat generation and convective cooling using finite element analysis software.
2. Model the steady-state heat conduction through an exhaust pipe wall with convection to the surrounding air, formulate the 1D conduction element and determine the temperature distribution

Exemplars / Practical Applications

1. Thermal analysis of an air-cooled motorcycle engine
2. Conduction and convection analysis of an automotive radiator assembly

3. Thermal management analysis of an EV battery system

Unit IV	Special Purpose Finite Elements for Real World Applications	06 Hours

Multipoint constraints, penalty method for the enforced displacements, kinematic coupling with one independent & multiple dependent nodes, distributing couplings with a single dependent and multiple independent nodes, tie constraints for connecting independently meshed components, point-mass elements with inertia matrices, dashpot element, modeling of joints including hinge, cylindrical & thrust bearing, beam elements with offsets, connecting 1D elements with 3D elements, automotive applications using finite element analysis software.

Real World Assignment

1. Create a finite element model of interfacing of MacPherson strut connection with the with the control arm bushing using a special purpose element. Apply appropriate loads and boundary conditions and verify results.
2. Develop a finite element model to transfer loads from the wheel center to the wheel hub using an appropriate connector element. Apply appropriate loads and boundary conditions and verify results.
3. Develop a FEA model for a weld element joining two sheet metal parts. Apply appropriate loads and boundary conditions and verify results.

Exemplars / Practical Applications

1. Modeling of car seats in a vehicle system model with concentrated mass, inertia matrix, and connecting with a BIW with distributing coupling for finite element analysis
2. Modeling road profile with enforced displacement boundary conditions to simulate a vehicle going over bumps
3. Modeling MacPherson struct in a vehicle with dash pot element

Unit V	Design of Experiments and Engineering Applications	09 Hours

Introduction to Design of Experiments (DoE) and its significance with real-world case studies, comparison of DoE and conventional optimization techniques, limitations of one-factor-at-a-time experimentation, controlled and uncontrolled factors, levels, and responses, design of experiments using full-factorial and fractional-factorial designs, introduction to screening DoE, Taguchi methods, and Plackett–Burman designs, identifying significant factors and interactions, determination of optimum factor settings, response surface generation & analysis, what-if studies, & trade-off analysis, optimization using response surface models, introduction to analysis of variance (ANOVA), case studies involving DoE applications to automotive engineering problems, DoE analysis using numerical computing or DoE software, evaluating responses using finite element analysis software or through physical experimentation.

Real World Assignment

1. Design an experiment varying resin-to-fiber ratio, curing pressure, and curing time to find the ideal recipe for maximum flexural strength in fiberglass or bio-composites. Alternatively, formulate a similar DoE problem to optimize the number of composite plies, fiber orientations, and material properties, and perform analysis using finite element analysis software.
2. Run a Taguchi array DoE varying spindle speed, feed rate, and depth of cut to minimize surface roughness on aluminum workpieces. Alternatively, solve a similar machining problem using a closed-form analytical solution or numerical simulation.

Exemplars / Practical Applications

1. Perform a DoE study for setting the best process parameter values for a high pressure Die casting machine including the fill time, velocity of plunger, and Die cooling time to reduce the rejection levels
2. Perform DoE for selecting the best combination of engine mounts with different stiffness in x, y, and Z directions and different orientation to reduce the engine vibration
3. Perform DoE to determine the optimal powder-coating process parameters, including powder properties, gun-to-part distance, part temperature, and spray pattern, to achieve high-quality surface finishes at minimum cost

Learning Resources
Text Books 1. Introduction to finite element in Engineering, T.R. Chandrupatla & A.D. Belegundu, 4th edition, Pearson 2. Basics of the finite element method- Solid mechanics, heat transfer, and fluid mechanics, P.E. Allaire, Wm. C. Brown Publisher 3. Textbook of finite element analysis, P. Seshu, PHI Learning Pvt. Ltd. 4. Statistics For Experimenters- An Introduction to Design, Data Analysis, and Model Building, George E.P. Box, W.G. Hunter, and J.S. Hunter, Wiley-Interscience, John Wiley & Sons, Inc.
Reference Books 1. Theory of vibration with applications, W.T. Thomson, CBS publications 2. Concepts and applications of finite element analysis, R.D. Cook, D.S. Malkus, M.E. Plesha, and R.J. Witt, 4th edition, John Wiley & Sons 3. Introduction to optimal design, J.S. Arora, 4th edition, Elsevier Science Publishing Co. Inc. 4. Engineering optimization theory and practice, S.S. Rao, New Age International Publisher
Web references
1. Prof. Nachiketa Tiwari, IIT, Kanpur, NPTEL Video- Basics of Finite Element Analysis https://www.youtube.com/watch?v=UOp6JEiJctA&list=PLSGws_74K018SmggufD-pbzG3thPIpF94

Savitribai Phule Pune University
Third Year of Mechanical Engineering (2024 Pattern)

HVSE352MEC: Simulations-based Design and Analysis Lab

Teaching Scheme		Credit	Examination Scheme	
Theory	NA	2	TW	25 Marks
Practical	4 Hours/Week		OR	25 Marks

- **Prerequisites:**

Solid Mechanics, Design of Machine Elements, Engineering Simulations and Analysis, Fundamentals of Machine Design and Optimization, Finite Element Analysis and Design of Experiments

Course Objectives:

After completing this course, students will be able to:

1. **DEVELOP** skills in formulating and solving engineering problems using finite element method
2. **APPLY** finite element techniques to analyze real-world structural, thermal, fluid-flow, and mechanical systems
3. **ENABLE** the development of simplified finite element models that capture real-world phenomena and facilitate effective engineering analysis.
4. **ENABLE** interpretation of FEA results and verification through hand calculations to validate the accuracy of numerical simulation tools.
5. **APPLY** Design of Experiments (DoE) and simulation-based methods for engineering design optimization and decision-making.

Course Outcomes:

After successful completion of the course, learner will be able to:

CO1: FORMULATE AND SOLVE basic structural, thermal, and fluid-flow problems using direct method and using commercial finite element software

CO2: DEVELOP simplified finite element models of real-world structural systems to accurately capture and analyze their response

CO3: ANALYZE finite element results to determine displacements, stresses, strains, forces, and support reactions and guide the design

CO4: LEARN applications of special elements such as kinematic & distributing coupling, beam with offsets, and MPCs to solve real world problems

CO5: APPLY full- and fractional-factorial DoE techniques with FEA to determine significant parameters, response surfaces, and balanced optimum designs

Guidelines for Conducting Laboratory Experiments

The student shall complete the following hands-on activities as a Term Work under the guidance of concerned faculty member. The open-source software shall be preferred for conducting practical sessions.

List of Laboratory experiments

All experiments are compulsory

Experiment 1: Pipe Network Analysis

Formulate and solve a three-pipe network with a Y-shaped configuration using the Abaqus, Ansys, Scilab, MATLAB, or any other software and direct method, assuming laminar flow. Assume appropriate values for pipe lengths and diameters in meters, fluid viscosity N.sec/m^2, and fluid density kg/m^3. Given the pressure in N/m^2 at the network inlet and at the two outlet points in N/m^2, determine the pressure in N/m^2 at the Y-junction and the flow rates in m^3/sec in the pipes. Use the direct approach for element & global matrix and obtain the solution using hand calculations and verify the results with numerical computing or finite element analysis software.

Exemplars / Practical Applications:

1. Simulate and design the fuel distribution network of an automobile
2. Simulate and design the lubricating oil distribution network for an automotive system
3. Simulate and design the water-cooling network for high-pressure die-casting dies

Experiment 2: Finite Element Analysis of a Real-World Truss Structure

Develop a simplified finite element model of a real-world truss structure located in a workshop or other suitable location. Compare a real-world truss structure photograph with its finite element model and identify the key modeling assumptions and approximations. Estimate the structural dimensions, cross-sectional properties, material properties, and support conditions. Assume pin connections between the members. Model the truss using a suitable finite element analysis software and subject it to extreme wind loading conditions to determine the maximum forces developed in the truss members and at the supports. Evaluate the resulting deflected shape and member stresses and assess the structural safety. Validate the forces and reaction forces obtained using finite element results through hand calculations. Analyze the same truss by assuming welded joints and compare the results with those obtained for riveted connections.

Exemplars / Practical Applications:

1. Finite element analysis of space-frame structures used in sports arenas
2. Structural analysis of cricket stadium roof structures under various loading conditions
3. Structural analysis of the Wimbledon center court retractable roof for safety and stability assessment
4. Structural analysis of an aircraft hangar frame

Experiment 3: Finite Element Analysis of a Motorcycle Frame

Develop a 3-D finite element model with beam elements of a real-world motorcycle frame. Measure geometric dimensions and estimate material properties, cross-sectional properties, and boundary conditions. Assume the rider mass and estimate the suitable equivalent static load for the motorcycle going through a pothole event. Model motorcycle engine as a concentrated mass with inertia matrix and connect with the frame appropriately. Perform a linear static finite element analysis to determine the deformed shape, stresses, and the factor of safety considering durability load. Find out the fundamental frequency of the motorcycle frame. Model the same motorcycle frame with shell elements and do the finite element analysis with the same loads and boundary conditions. Compare the finite element results obtained using beam and shell element models with respect to stress distribution and deformation, and evaluate the differences in their predictions.

Exemplars / Practical Applications:

1. Truck ladder-frame finite element analysis for NVH and durability performance assessment
2. Truck cabin structural analysis for durability and crashworthiness evaluation
3. Formula 1 race car analysis to evaluate bending stiffness, torsional stiffness, and fundamental natural frequencies
4. Crane frame and lifting-arm finite element analysis to determine maximum load-carrying capacity and structural safety

Experiment 4: Finite Element Analysis of a Heat Convection Problem

A composite wall consists of 4 materials with the wall thickness t_1, t_2, t_3, and t_4 defined in meters with different thermal conductivity coefficients of k_1, k_2, k_3, and k_4 in W/m^0C. The outer temperature is T_0 ^0C. Convection heat transfer take place in the inner surface of the wall with $T_\infty$$^0C$ and heat transfer coefficient h $W/m^2.^0C$. Determine the temperature distribution in the wall. Make assumptions for the numerical values as appropriate. Use penalty approach to enforce the temperature condition. Formulate the FEA problem with 4 elements and construct the element and global matrix with hand calculations and solve the simultaneous equations with numerical computing software. Solve the same problem using a finite element analysis software and verify the answers with hand calculations.

Exemplars / Practical Applications:
1. Refrigerator or freezer wall insulation analysis
2. Industrial furnace wall thermal analysis
3. Aircraft cabin thermal insulation analysis
4. Electric vehicle battery enclosure thermal analysis

Experiment 5: Comparison of Kinematic and Distributing Coupling

Develop a finite element model of a cantilever beam with a Z-shaped cross-section using shell elements. Apply a vertical point load at the free-end face through two different approaches: (i) kinematic coupling between a reference point, located at the C.G. at the free end, and the nodes on the free-end face, and (ii) distributing coupling between the reference point, located at the C.G. at the free end, and the nodes on the free-end face. The reference point can be chosen at the center of the beam at the free end. Assume suitable dimensions, material properties, and load for the analysis. Perform static finite element analyses for both modeling approaches and compare the resulting deformed shapes, displacements, stress distributions, and load-transfer characteristics. Discuss the differences in the results and the behavior of the load distribution on the end face of the beam. Use finite element software for modeling and analysis.

Exemplars / Practical Applications:
1. Simulating clamping pressure on a Die mounted on a HPDC machine
2. Simulate an HVAC system using a lumped-mass model and connect it to the vehicle body using special elements
3. Transfer engine loads from a reference point to the mounting bracket while ensuring realistic load distribution

Experiment 6: Analysis of a 3D Frame Structure Modeled using Beams with C.G. Offset from the Nodes

Analyze a real-world 3D frame structure fabricated by welding steel sections of different cross-sectional sizes, such as structures commonly used at building entrances. The beams should intersect to form a 3D rigid structural assembly. Model the structure using beam elements with appropriate offset, to account for the offset of the C.G. location away from the node position. Apply static loads representing realistic load cases, such as the accidental impact of a crane with the structure. Perform the analysis considering self-weight and evaluate the resulting stresses, deformations, and support reactions.

Exemplars / Practical Applications:
1. Analyze a simplified vehicle model using beam, shell, and spring elements
2. Analyze a truck ladder frame modeled using beam elements with offsets
3. Analyze a crane structure modeled using beam elements with offsets

Experiment 7: Design of a Motorcycle Handle Bar Using Design of Experiments (DoE)

Perform a Design of Experiment (DoE) for a motorcycle handlebar to minimize weight and minimize the displacement subject a point load at the free end. Use realistic dimensions, material properties, and loading conditions, and model the handlebar as a hollow tube using shell elements as a cantilever beam. Consider three factors at two levels for the DoE: tube outer diameter, tube thickness, and tube design (shape). Consider two alternative handlebar designs based on aesthetics and packaging constraints. Construct a full-factorial DoE, perform analysis using a finite element software, & calculate significant main effects and interactions using response surfaces, identify the critical parameters and optimum levels for each response. Determine a balanced design by evaluating the weight–displacement trade-off. Use DoE software to set up the experiment, calculate and visualize main effects, interactions, and response surfaces. Verify DoE software results with hand calculations. Use numerical computing or DoE software for designing the experiment and for data analysis. Design a fractional factorial DoE and compare the resulting response surface with that obtained from a full factorial design. Discuss the advantages and limitations of fractional-factorial designs. Discuss pros and cons if we would have considered a 3-level DoE instead of 2-level DoE.

Exemplars / Practical Applications:

1. Perform DoE to determine the optimal process parameters for gear manufacturing
2. Perform DoE to determine the optimal process parameters for plastic injection molding

Learning Resources

Text Books

1. Introduction to finite element in Engineering, T.R. Chandrupatla & A.D. Belegundu, 4th edition, Pearson
2. Basics of the finite element method- Solid mechanics, heat transfer, and fluid mechanics, P.E. Allaire, Wm. C. Brown Publisher
3. Textbook of finite element analysis, P. Seshu, PHI Learning Pvt. Ltd.
4. Statistics For Experimenters- An Introduction to Design, Data Analysis, and Model Building, George E.P. Box, W.G. Hunter, and J.S. Hunter, Wiley-Interscience, John Wiley & Sons, Inc.

Reference Books

1. Theory of vibration with applications, W.T. Thomson, CBS publications
2. Concepts and applications of finite element analysis, R.D. Cook, D.S. Malkus, M.E. Plesha, and R.J. Witt, 4th edition, John Wiley & Sons.
3. Introduction to optimal design, J.S. Arora, Elsevier Science Publishing Co. Inc.
4. Engineering optimization theory and practice, S.S. Rao, New Age International Publisher

Savitribai Phule Pune University, Pune

Maharashtra, India

BE - Mechanical Engineering
(2024 Pattern)

SEMESTER- VII

Honor Courses

[Vehicle Subsystem Engineering]

Savitribai Phule Pune University
Final Year of Mechanical Engineering (2024 Pattern)

HVSE401MEC: Fundamentals of Low Frequency NVH and Automotive Applications

Teaching Scheme		Credit	Examination Scheme	
Theory	**3 Hours/Week**	**3**	**CCE**	**30 Marks**
Practical	**NA**		**End-Semester**	**70 Marks**

- **Prerequisites:**

Solid Mechanics, Design of Machine Elements, Dynamics of Machinery, Fundamentals of Machine Design and Optimization, Finite Element Analysis and Design of Experiments

Course Objectives:

After completing this course, students will be able to:

1. **ACQUIRE** in-depth knowledge of finite element-based simulation techniques for low-frequency vibration problems and an overview of methodologies for mitigating NVH issues
2. **LEARN** to represent complex real-world vehicle NVH problems using simplified vehicle models to develop a fundamental understanding of the problem and the associated modelling techniques
3. **LEARN** finite element formulations for multi-degree-of-freedom eigenvalue, harmonic, and transient dynamic analyses to predict vibration responses under various loading conditions, including road inputs, tire imbalance, and engine-induced excitations
4. **INTRODUCE** experimental techniques for measuring noise and vibration, along with methods for signal processing and data analysis
5. **LEARN** the application of finite element-based modelling and NVH optimization techniques to solve vibration problems at both the concept and detailed design stages

Course Outcomes:

After successful completion of the course, learner will be able to:

CO1: LEARN to develop simplified vehicle models using finite element approaches, including 1-DoF, 2-DoF, & 4-DoF, and multi-degree-of-freedom models

CO2: LEARN finite element formulations for multi-degree-of-freedom eigenvalue problems and damping techniques to determine natural frequencies and mode shapes

CO3: LEARN finite element formulations for harmonic and transient dynamic analyses to simulate responses such as seat-track vibration and steering-column vibration for improved customer comfort

CO4: FORMULATE optimization problems using commercial NVH simulation software to optimize the design and mitigate vibration problems through sizing, shape, topology, and topography optimization

CO5: GAIN EXPOSURE to various advance techniques such as multifunctional optimization, modal alignment, and signal analysis to mitigate NVH problems at concept and detailed design level

Course Contents

Unit I	Introduction to NVH and automotive applications	05 Hours

Definition of Noise, Vibration, and Harshness (NVH), NVH regulatory standards, EHS, sustainability, & customer requirements, NVH target setting, attribute engineering, test versus CAE correlation & challenges, powertrain noise, cabin booming noise, suspension noise, motor whine, gear rattle, brake squeal, concept level development, NVH problem solving with source-path-effect methodology & case studies, classification of NVH problems based on low, mid, and high frequency range, time domain and frequency domain problems, finite element based NVH analysis & optimization process, fundamental assumptions in low frequency linear dynamic analysis, Maxwell-Betti reciprocal theorem in structural & vibration analyses, mass moment of inertia matrix & conversion to principal inertia and axes using eigenvalue problem, airborne & structure-borne noise, mastic treatment for BIW, power spectrum density analysis and applications.

Real World Assignment

1. Apply the source–path–effect methodology to identify, isolate, and diagnose vibration issues at the vehicle seat track.
2. Explain the differences in damping characteristics between the compression and rebound strokes of a MacPherson strut in a four-wheeler.
3. Measure seat-track vibration levels using a smartphone's built-in accelerometer while driving a four-wheeler over a rumble road at low and high speeds. Analyze the recorded vibration signals and compare seat-track acceleration levels at different speeds to identify response frequencies and vibration isolation.

Exemplars / Practical Applications

1. Apply the source–path–effect methodology to identify the root causes of passenger-compartment boom
2. Mitigate steering-column vibration by using modal alignment charts
3. Reduce high-frequency noise in the passenger compartment by applying appropriate mastic damping treatments
4. Develop an anechoic chamber and conduct sound-pressure mapping

Unit II	Fundamentals of Noise and Vibration	07 Hours

Relationship between the vehicle speed and road excitation frequency, root cause analysis of NVH problems with examples, various types of NVH loads on the vehicle including engine, electromagnetic forces, road excitation, order of vibration, difference between peak to peak, max amplitude, and RMS response for a signal, threshold of hearing, reference sound pressure, Euler's formula, real & imaginary versus amplitude and phase representation for the vibration, sound level meter, dosimeters, difference between sound pressure, sound intensity, and sound power & its applications, transverse and longitudinal sound waves, 1/1, 1/2, & 1/3rd octave bands, psychoacoustics, measuring sound in sones and phones, loudness of sound, equal loudness contours as per ISO 226, A-B-C-D sound pressure weighting, NVH ratings based on sones and phones, vibration severity rating based on the velocity versus frequency

Real World Assignment

1. Record passenger-compartment noise using a microphone and analyze the measured sound using 1/1-, 1/2-, and 1/3-octave band frequency analysis.
2. Generate and play pure tones at an 80 dB sound pressure level at selected 1/3-octave center frequencies using a freeware in a quiet room. Ask participants to rate the perceived loudness of each tone over the frequency range of 20 Hz to 12 kHz. Compare the subjective loudness ratings with the A-weighted sound pressure levels to study the influence of frequency on human auditory perception.

Exemplars / Practical Applications

1. Subjective evaluation of seat-track vibration levels
2. Subjective evaluation of sound pressure levels inside the passenger compartment
3. Measure sound pressure levels using a sound level meter to assess environmental noise levels

Unit III	Finite Element Formulation for Multi-degrees of Freedom Eigenvalue Problems	10 Hours

Introduction to Hamilton's principle, principle of minimum potential energy, derive the mass matrix using the shape functions for 1D and 2D elements- spring, mass, truss, beam, and CST, and quadrilateral elements, global stiffness & mass matrix, consistent mass versus lumped mass matrix & approximations, mathematical modeling of elastomers with dynamic stiffness with frequency dependent characteristics, harmonic excitation- wheel unbalance, speed breakers, engine unbalance, formulation of real eigenvalue problem for multi-degree-of-freedom problems, orthogonal properties of eigenvectors, Raleigh quotient, generalized mass, generalized stiffness & generalized force vector, consistent mass matrix and lump mass matrix, significance of rigid body modes and applications.

Real World Assignment

1. Perform a modal analysis of an automotive hood to determine its fundamental natural frequency and mode shape.
2. Perform a modal analysis of a motorcycle frame to determine the natural frequencies and mode shapes, including rigid body modes.
3. Perform a modal analysis of a tall advertising-board support structure to determine its first natural frequency and assess whether it is close to the expected wind-induced excitation frequency, thereby evaluating the potential for resonance.

Exemplars / Practical Applications

1. Modal analysis of a Body-In-White
2. Experimental modal analysis of a truck chassis
3. Experimental modal analysis of an aircraft wing
4. Modal analysis of a satellite

Unit IV	Finite Element Formulation for Multi-degrees of Freedom Forced Harmonic and Transient Dynamic Problems	09 Hours

Finite element formulation of multi-degree-of-freedom systems using mode superposition and direct methods for forced harmonic and transient dynamic analyses, transformation between physical coordinates and modal coordinates, definition of modal mass, modal stiffness, & modal force, effective mass, modal contribution factor, modal participation factor, Nyquist criterion and selection of cut-off frequency for mode superposition method, types of damping including modal, Rayleigh, viscous, and structural damping, finite element formulation of damped multi-degree-of-freedom systems for harmonic and transient analyses, sprung and unsprung masses, quarter car & half car models, vibration isolation & dampers, resonance frequencies & mode shapes, modal alignment charts, trade-off between NVH and vehicle dynamics.

Real World Assignment

1. Perform a forced-frequency response analysis of an automotive component over the 0–150 Hz range using both the modal superposition and direct frequency-response methods. Apply the Nyquist criterion to determine an appropriate modal cutoff frequency and compare the responses obtained using both approaches. Evaluate the effect of selecting 100 Hz as the cutoff frequency on the accuracy of the predicted response.
2. Develop a half-car dynamic model representing a real-world vehicle by estimating key parameters, including vehicle sprung & unsprung masses, front and rear suspension stiffness, tire stiffness, and wheel–tire assembly masses. Determine the vehicle ride and wheel-hop frequencies, and evaluate the vibration response at the driver's seat location as the vehicle goes over speed bumps at different speeds.

Exemplars / Practical Applications

1. Perform finite element analysis of a vehicle subjected to wheel-unbalance excitation and evaluate vibration response at the seat-track
2. Perform Power Spectral Density (PSD) analysis of a vehicle to evaluate vibration responses at the steering-column
3. Perform a dynamic analysis of a turbine blade to determine its vibration characteristics and response under operational loading
4. Evaluate the vibration response at the motorcycle rider's seat while traversing a railway crossing

Unit V	NVH Optimization for Multi-degrees of Freedom FE Models and Advanced Topics in NVH	08 Hours

Formulation of multi-variable and multi-constraint finite element-based optimization problems with design variables including sizing parameters such as panel thickness, spring stiffness, and mass, shape variables for the geometry, topology, and bead optimization, formulation of NVH and static objective function & constraints including bending stiffness, torsional stiffness, natural frequency, and tactile response, case studies on sizing, shape, topology, and bead optimization using NVH objective function and constraints using finite element analysis software, Advanced topics in NVH - point mobility, transfer function analysis, introduction to vibroacoustic analysis using fluid–structure interaction for prediction of noise and vibration using finite element methods, experimental measurement of noise and vibration using DAQ, accelerometers, & microphones, modal testing using impact hammer and shakers, Operational Deflected Shapes (ODS) and applications, order analysis, waterfall plots, orbit plots, and Campbell diagrams, manufacturing & material variability and robust design, design sensitivity analysis and multifunctional optimization

Real World Assignment

1. Perform topology optimization of an engine mounting bracket to achieve weight reduction while satisfying structural performance requirements.
2. Perform topology optimization of a car hood under different loading conditions to determine the optimal layout of the hood inner panel.
3. Perform bead optimization of a car body to maximize its fundamental natural frequency while meeting design constraints.

Exemplars / Practical Applications

1. Perform sizing optimization of a Body-in-White (BIW) structure to reduce weight and maintain noise and vibration responses across various load cases and frequencies

2. Perform shape optimization of an engine mounting bracket and reduce weight
3. Perform bead optimization of an automotive floor panel to maximize structural stiffness while maintaining the required design and manufacturing constraints.

Learning Resources

Text Books

1. Introduction to finite element in Engineering, T.R. Chandrupatla & A.D. Belegundu, 4th edition, Pearson
2. Theory of vibration with applications, W.T. Thomson, CBS publications
3. Fundamentals of acoustics, L.E. Kinsler, A.R. Frey l, A.B. Coppens, and J.V. Sanders, John Wiley & Sons
4. Handbook of Noise Measurement, Arnold P.G. Peterson, GenRad Inc.
5. Introduction to optimal design, J.S. Arora, 4th edition, Elsevier Science Publishing Co. Inc.

Reference Books

1. Concepts and applications of finite element analysis, R.D. Cook, D.S. Malkus, M.E. Plesha, and R.J. Witt, 4th edition, John Wiley & Sons
2. Mechanical Vibrations, G.K. Grover, Nem Chand & Brothers
3. Mechanical Vibrations, S. S. Rao, Pearson
4. Elements of structural optimization, R.T. Haftka and G. Zafer, Springer
5. Practical optimization methods, M. Asghar Bhatti, Springer

Web References:

1. Prof. A.K. Darpe, IIT, Delhi, NPTEL Video- Elements of Mechanical Vibrations
https://www.youtube.com/watch?v=nWM5gg3SkEI&list=PLp6ek2hDcoNBihD_JCzIvc-t_gApqMGKd
2. Prof. S.V. Modak, IIT, Delhi, NPTEL Video- Experimental Modal Analysis
https://www.youtube.com/watch?v=tzhSU9CTl08&list=PLp6ek2hDcoNBDFAjQQns7Gj0kYnKglwIr
3. Prof. Shakti Gupta and Prof. Mohit Law, IIT, Kanpur, KIT Video- Modal Analysis
https://www.youtube.com/watch?v=3gYUFRmkeh8&t=2022s

Savitribai Phule Pune University Final Year of Mechanical Engineering (2024 Pattern)				
HVSE402MEC: Vehicle Vibration Analysis Lab				
Teaching Scheme		**Credit**	**Examination Scheme**	
Theory	**NA**	**2**	**TW**	**25 Marks**
Practical	**4 Hours/Week**		**OR**	**25 Marks**

- **Prerequisite courses:**

Solid Mechanics, Design of Machine Elements, Dynamics of Machinery, Fundamentals of Machine Design and Optimization, Finite Element Analysis and Design of Experiments, Fundamentals of Low Frequency NVH and Automotive Applications

Course Objectives:

After successful completion of the course, learner will be able to:

1. UNDERSTAND fundamental vibration and dynamic phenomena through hands-on experiments involving mechanical and vehicle systems
2. APPLY experimental techniques for measuring vibration and acoustic responses using DAQ systems and sensors
3. ANALYSE vibration and noise signals in both time and frequency domains to identify natural frequencies, resonances, harmonics, phase relationships, and damping characteristics
4. DEVELOP finite element and analytical models of mechanical and automotive systems to predict modal and forced vibration responses and validate them against experimental results
5. APPLY structural optimization techniques such as topology, sizing, and bead optimization to improve the dynamic performance and reduce the weight of automotive components

Course Outcomes:

After successful completion of the course, learner will be able to:

CO1: EVALUATE the dynamic behavior of mechanical and vehicle systems through laboratory experiments and determine their natural frequencies, mode shapes, and resonance characteristics

CO2: MEASURE AND INTERPRET vibration and acoustic responses using DAQ systems, accelerometers, microphones, FFT, waterfall plots, and other signal-processing techniques

CO3: DEVELOP AND VALIDATE analytical and finite element models for vehicle and structural vibration problems, including quarter-car, half-car, and forced-response systems

CO4: ANALYSE vehicle ride, wheel-hop, bounce, pitch, beat phenomena, and NVH characteristics under harmonic and road-induced excitations

CO5: FORMULATE AND SOLVE structural optimization problems using topology, sizing, and bead optimization techniques to improve stiffness, natural frequency, and dynamic performance while reducing component weight

Guidelines for Conducting Laboratory Experiments

The student shall complete the following hands-on activities as a Term Work under the guidance of concerned faculty member. The open-source software shall be preferred for conducting practical sessions.

All experiments are compulsory

Experiment 1: Transient Dynamic Test of a Spring Mass System

Perform an experiment for a spring–mass system consisting of a rubber band and a concentrated mass to investigate the effect of mass variation and ground excitation on the natural frequency and forced frequency response. Examine the influence of different initial conditions on the dynamic response, record the motion using a mobile camera, and analyze the recorded response to determine the damped natural frequency, logarithmic decrement, and damping ratio. Investigate the effect of ground excitation, for the rubber band and mass system, on the vibration response of the mass.

Exemplars / Practical Applications:
1. Study vehicle response while going over a bump
2. Study the effect of added mass and support stiffness on its natural frequency of a Body-In-White
3. Optimize engine mounts to improve engine vibration isolation

Experiment 2: Electric Motor Noise Analysis

Measure and record the acoustic noise generated by an electric motor during an RPM sweep using a DAQ system with a microphone. Analyze the recorded noise data using numerical computing or NVH analysis software to identify resonances, orders, harmonics, and their corresponding frequency characteristics. Interpret and document the experimental results.

Exemplars / Practical Applications:
1. Electric vehicle motor noise characterization
2. HVAC blower noise analysis
3. Radiator fan noise analysis
4. Compressor noise analysis

Experiment 3: Vibration Analysis of a Quarter Car Test Rig with Ground Excitation

The objective of the experiment is to study the vibration characteristics of a 2-degree-of-freedom quarter-car test rig subjected to harmonic road excitation at the ground level at different frequencies and determine the ride and wheel-hop resonance frequencies and the corresponding forced vibration response. Students should acquire the vibration responses of the sprung and unsprung masses using a Data Acquisition System (DAQ) and accelerometers. Analyze the data in the frequency domain to identify resonance frequencies and measure accelerations and phase angles. Also analyze the data in the time domain using waterfall charts.

Exemplars / Practical Applications:
1. Vehicle suspension tuning
2. Evaluating effect of tyre stiffness on seat track vibration
3. Vehicle speed analysis and its effect on steering column vibration
4. Experimental validation of a vehicle dynamics model

Experiment 4: Vibration Analysis of a Half Car Test Rig with Ground Excitation

The objective of the experiment is to study the vibration characteristics of a 4-degree-of-freedom (4-DOF) half-car test rig subjected to harmonic road excitation, i.e., ground excitation at different speeds and determine the bounce & pitch frequencies, wheel-hop frequency, and the corresponding forced vibration response. Students should acquire the vibration responses of the sprung and unsprung masses using a Data Acquisition System (DAQ) and accelerometers. Analyze the data in the frequency domain to identify resonance frequencies and measure accelerations and phase angles.

Exemplars / Practical Applications:
1. Front and rear suspension tuning
2. Vehicle pitch analysis during braking and acceleration
3. Vehicle speed optimization for ride performance
4. Effect of payload distribution on vehicle dynamics

Experiment 5: Vibration Analysis of a Structure Using a Shaker Table

The objective of this experiment is to measure the response of a single-story building subject to horizontal ground motion and analyze the frequency response. A single-story building (scaled model) with steel columns and floor, representing a real-world building, is subjected to the ground motion representing earthquake loads. Perform an experiment and measure the resonance frequencies and forced frequency response. Design a mass damper or a vibration isolation system to reduce the vibration of the building and verify the solution. Use a Data Acquisition System (DAQ) and accelerometers to record the responses and analyze the responses using FFT, water fall plots and other techniques.

Exemplars / Practical Applications:
1. Seismic response of buildings
2. Tuned mass damper design
3. Vibration isolation of structures

4. Vibration control of structures

Experiment 6: Beat Phenomenon

The objective of this experiment is to determine the vibration frequencies of two coupled pendulums connected by a spring and study their response to different initial displacements or velocities. Experimentally determine the beat frequency and carrier frequency from the oscillatory response, and verify the experimental results through analytical calculations or simulations. Identify the 2 natural frequencies and mode shapes of the system and transient dynamic response. Extend the experiment to three- and four-pendulum systems to investigate and identify their resonance frequencies & beat phenomenon.

Exemplars / Practical Applications:

1. FM and AM radio
2. Engine noise
3. Rotating machinery and fault diagnosis

Experiment 7: Measuring Natural Frequencies and Mode Shapes of a String using Ground Excitation

The objective of this experiment is to determine the natural frequencies and mode shapes of a vibrating string. A simple experimental setup can be developed using a speaker, a string maintained at a specified tension, and a variable-frequency excitation source. Perform a frequency sweep to identify the natural frequencies and corresponding mode shapes, and validate the experimental results using finite element analysis software.

Exemplars / Practical Applications:

1. Stringed musical instruments
2. Timing and drive belt
3. Tire and belt reinforced structures

Experiment 8: Forced Frequency Response Simulation of a 1-DoF Quarter Car Model

Develop and simulate forced frequency response of a 1-degree-of-freedom (1-DOF) quarter-car finite element model, representing a real world 4-wheeler. Define appropriate values of the sprung mass, suspension stiffness, and viscous damping coefficient based on a representative vehicle. Define the harmonic loads on the sprung mass and perform harmonic analysis using finite element analysis software. Determine the natural frequency, damped natural frequency, displacement, velocity, and acceleration versus frequency response & phase angle. Compare the simulation results with the hand calculations.

Exemplars / Practical Applications:

1. Ride comfort analysis
2. Suspension and damper optimization
3. Road induced vibration analysis

Experiment 9: Ground Motion Simulation of a 2-DoF Quarter Car Model

Develop and simulate a 2-degree-of-freedom (2-DOF) quarter-car finite element model, representing a real world 4-wheeler car, travelling over a rumble road at different speeds and analyze the response. Define appropriate values of the sprung and unsprung masses, suspension and tire stiffness, and viscous damping coefficients, based on a representative vehicle. Model the rumble road as a sinusoidal ground excitation of constant amplitude and perform normal mode analysis using finite element analysis software to determine the natural frequencies & mode shapes. Perform forced vibration analysis using the modal superposition method to determine the frequency response of the sprung and unsprung masses over a range of excitation frequencies. Evaluate and interpret the resonance frequencies, vibration amplitudes, and phase angle for sprung and unsprung masses.

Exemplars / Practical Applications:
1. Tire and wheel-hop dynamics analysis
2. Front and rear suspension tuning to minimize pitch motion
3. Suspension travel and packaging space optimization

Experiment 10: Topology Optimization of a Motorcycle or Scooter Footrest

Perform topology optimization to maximize the first natural frequency of a motorcycle or scooter footrest and reduce the component weight by 40%. Develop a finite element model of a real-world motorcycle or scooter footrest using solid elements and define the design region. Define appropriate material properties, geometric dimensions, boundary conditions, and loading conditions. Perform topology optimization to maximize the first natural frequency of the footrest and reduce the weight by 40%. Interpret the topology optimization results and modify the geometry and do reanalysis to verify the results. Use finite element analysis software for vibration analysis and topology optimization.

Exemplars / Practical Applications:
1. Steering column bracket optimization
2. Knuckle optimization
3. Control arm optimization

Experiment 11: Sizing Optimization of a Cantilever Beam Box Section

Perform sizing optimization of a cantilever beam with a box cross-section modeled using shell elements, with the objective of maximizing the beam stiffness while achieving a 25% reduction in weight. Apply a uniformly distributed static load along the top surface of the beam together with a concentrated load at the free end. Divide the beam along its length into 10 sections and define the shell thicknesses of these sections as the design variables. Formulate and solve the sizing optimization problem, and evaluate the optimized thickness distribution and interpret & document the results. Use finite element analysis software for static analysis and sizing optimization.

Exemplars / Practical Applications:
1. Body structure optimization
2. Chassis design
3. Aircraft structural weight reduction
4. Door weight optimization

Experiment 12: Bead Optimization of a Fuel Tank

Develop a simplified finite element model of shell elements for a four-wheeler fuel tank, representing a realistic automotive component. Do not put beads on the surface while you prepare a shell element model of a fuel tank. Perform bead optimization of a fuel tank with the objective of increasing its first natural frequency with the constraint on the bead height. Assume suitable geometric dimensions, material properties, and boundary conditions. Verify the results with reanalysis. Use finite element analysis software for vibration analysis and optimization.

Exemplars / Practical Applications:
1. Battery tray optimization
2. Vehicle floor panel optimization
3. Package-tray optimization
4. Hood outer panel optimization

Learning Resources

Text Books

1. Introduction to finite element in Engineering, T.R. Chandrupatla & A.D. Belegundu, 4th edition, Pearson
2. Theory of vibration with applications, W.T. Thomson, CBS publications
3. Fundamentals of acoustics, L.E. Kinsler, A.R. Frey l, A.B. Coppens, and J.V. Sanders, John Wiley & Sons
4. Handbook of Noise Measurement, Arnold P.G. Peterson, GenRad Inc.
5. Introduction to optimal design, J.S. Arora, 4th edition, Elsevier Science Publishing Co. Inc.

Reference Books

1. Concepts and applications of finite element analysis, R.D. Cook, D.S. Malkus, M.E. Plesha, and R.J. Witt, 4th edition, John Wiley & Sons
2. Mechanical Vibrations, G.K. Grover, Nem Chand & Brothers
3. Mechanical Vibrations, S. S. Rao, Pearson
4. Elements of structural optimization, R.T. Haftka and G. Zafer, Springer
5. Practical optimization methods, M. Asghar Bhatti, Springer

Savitribai Phule Pune University, Pune

Maharashtra, India

BE - Mechanical Engineering (2024 Pattern)

SEMESTER- VIII

Honor Courses

[Vehicle Subsystem Engineering]

Savitribai Phule Pune University
Final Year of Mechanical Engineering (2024 Pattern)

HVSE451MEC: Multibody Dynamics and Vehicle Dynamics

Teaching Scheme		Credit	Examination Scheme	
Theory	4 Hours/Week	4	CCE	30 Marks
Practical	NA		End-Semester	70 Marks

- **Prerequisite courses:**

Solid Mechanics, Design of Machine Elements, Dynamics of Machinery, Theory of Machines, Fundamentals of Machine Design and Optimization, Finite Element Analysis and Design of Experiments, Fundamentals of Low Frequency NVH and Automotive Applications

Course Objectives:

After completing this course, students will be able to:

1. **LEARN** fundamentals of planar and spatial multibody kinematics, constraints, joints, and motion analysis and INTRODUCE vehicle dynamics
2. **FORMULATE AND SOLVE** constrained multibody dynamic systems using analytical and numerical methods
3. **LEARN** multibody dynamics to automotive systems to analyse ride, handling, stability, and control
4. **INTRODUCE** tire mechanics, longitudinal dynamics, braking, and vehicle acceleration performance
5. **EVALUATE** vehicle lateral dynamics, cornering behavior, neutral steer, understeer, oversteer, and ride characteristics

Course Outcomes:

After successful completion of the course, learner will be able to:

CO1: DEVELOP kinematic models and determine position, velocity, and acceleration of constrained multibody systems

CO2: DEVELOP AND SOLVE dynamic models of planar and spatial multibody systems using MBD software

CO3: LEARN automotive suspension, steering, and vehicle systems for ride, handling, and stability

CO4: EVALUATE tire forces, braking, traction, acceleration, and longitudinal vehicle performance

CO5: PREDICT vehicle cornering and lateral response using a bicycle model and determine neutral steer, understeer, & oversteer characteristics

Course Contents

Unit I	Introduction to Multibody Planer Kinematic Systems	08 Hours

Introduction to kinematics, multibody dynamics, and vehicle dynamics with applications in the automotive industry, holonomic and nonholonomic constraints, review of 2D and 3D matrix algebra, rank of a matrix, orthogonality, and coordinate transformations, vector and matrix differentiation, position, velocity, and acceleration of a point in a moving reference frame, formulation of kinematic constraint equations in terms of generalized coordinates, Jacobian matrix, absolute constraints, distance and absolute position constraints, relative constraints, coordinate constraints, modeling of revolute and translational joints, composite joints, gears, and cam-follower mechanisms, driving constraints, absolute and relative drivers, position, velocity, and acceleration analysis using numerical examples and practical simulations with numerical computing or multibody dynamics simulation software.

Real World Assignment

1. Windshield wiper mechanism – Model the linkage and determine the angular displacement, velocity, and acceleration of the wiper blade for a prescribed motor speed.
2. Engine connecting-rod mechanism – Model the crank-slider mechanism and determine piston displacement, velocity, and acceleration as a function of crank angle.
3. Scissor jack mechanism – Model the lifting mechanism and calculate the vertical displacement and velocity of the lifting saddle point for a given screw rotation.

Exemplars / Practical Applications

1. Kinematic and compliance analysis of a corner unit
2. Kinematics of a folding boom in a space antenna
3. Motion of a robot arm

Unit II	Spatial Cartesian Kinematics	10 Hours

Reference frames for defining the position and orientation of bodies in 3-D space, coordinate transformations and direction cosine matrices, position, velocity, acceleration, and angular velocity, Euler parameters as generalized coordinates, Euler's theorem and properties of Euler parameters, relationship between Euler-parameter derivatives and angular velocity, kinematic constraints using joint definition frames, constraints on vectors and points, constraints involving parallel vectors between and on adjacent bodies, joint types and constraint equation- including cylindrical, spherical, universal, revolute, translational, & screw joints, absolute point constraints and distance constraints between pairs of bodies, composite joints- including spherical-spherical, revolute-revolute, revolute-cylindrical, and revolute-translational joints, driving constraints- relative translational and rotational drivers, Degrees of Freedom (DOF) for constrained multibody systems, Euler-parameter normalization constraint, numerical solution of kinematic constraint & drivers, formulation of velocity and acceleration equations, identification of DOF for various mechanisms and numerical solution of position, velocity, and acceleration analyses, & results interpretation, introduction to inverse kinematics and its applications, automotive applications using numerical computing or multibody dynamics software.

Real World Assignment

1. Study various joints for a corner module in a 4-wheeler and write down the constraint equations for joints. Draw the schematic of a corner unit.
2. Study independent rear suspension & kinematic motion of the rear wheels.

Exemplars / Practical Applications

1. Double-wishbone suspension – Simulate suspension travel and determine wheel-center motion
2. Constant-velocity (CV) joint – Develop a simplified 3-D model of a CV joint and study the relationship between input and output shaft rotation
3. Excavator boom and bucket – Develop a 3-D linkage model and determine bucket position and orientation for prescribed hydraulic-cylinder movements

Unit III	Multibody Planer Dynamics and Introduction to Vehicle Dynamics	10 Hours

Dynamics of Planar Systems: Variational equations of motion from Newton's equations, D'Alembert's principle, equations of motion for translational and rotational generalized coordinates, virtual work and generalized forces, modeling of translational springs, dampers, and actuators, formulation of equations of motion for constrained systems, variational formulation of planar multibody dynamics, Lagrange multipliers, mixed differential-algebraic equations (DAEs) of motion, initial conditions, inverse dynamics, equilibrium conditions, numerical examples and multibody simulations using numerical computing or multibody dynamics software; Vehicle Dynamics: achieving optimal ride comfort, handling, and stability, rigid-body versus flexible-body dynamics, vehicle stability and control systems- ABS, ESC, traction control, ADAS, four-wheel steering, & anti-roll bars, vehicle suspension systems, including active and semi-active suspensions, MacPherson strut, rear twist-beam, multi-link, and air suspension systems, body-on-frame versus unibody vehicle architectures, Influence of elastomers on vehicle ride and handling performance, wheel ratio and motion ratio, role of caster, camber, & toe, regulatory standards, DAQs and sensors for measurements and control, & road load data acquisition.

Real World Assignment

1. 2-D excavator boom analysis – Determine hydraulic-cylinder forces and joint reaction forces during boom operation.

2. Semi-active suspension study of motorcycles and passenger vehicles – Investigate motorcycles and four-wheelers available in the Indian market equipped with semi-active suspension systems and document their internal damping-control mechanisms based on publicly available information.

Exemplars / Practical Applications

1. Road load data aqusition & performing accelerated durability testing.
2. V2V communications for improved safety and controls
3. Active suspensions in 4W vehicles

Unit IV	Tyres and Longitudinal Dynamics	12 Hours

Radial and bias tyres, tire size and rating, contact patch, SAE tire axis system, load rating, mechanics of tyre force generation, tractive properties, slip, braking force verses slip, slip angle, rolling tire deformation under lateral force, lateral force versus slip angle, camber thrust, combined braking and corning, tire vibration, dynamic axle loads, loads on grades, vehicle acceleration performance- tractive force, tractive force versus speed, traction-limited acceleration, transvers weight shift due to drive torque, braking- constant deceleration, wind resistance, energy & power, braking forces- rolling resistance, braking deformation in the contact patch, braking forces versus deceleration, braking efficiency, front brake force versus rear brake force & lockup, slip, torque versus time- drum & disk brakes, regulatory standards for braking, introduction to tyre models, applications & limitations- brush, Pacejka, & magic formula models, applications using numerical computation or multibody dynamics software.

Real World Assignment

1. Given the weight of the vehicle, speed at the time brakes are applied, type of surface, and braking force, find out deceleration, stopping distance, time to stop, energy dissipated, and brake HP at initial application and averaged over the stop. Neglect aerodynamic and rolling resistance forces.
2. Consider a tire with the following parameters- vertical load, F_z, tire-road friction coefficient, μ, contact patch length, L in m., contact patch width, b in m., cornering stiffness in the linear region, C_α in N/rad. Determine the slip angle at which the tire reaches the maximum lateral force F_y. Plot F_y versus slip angle α and identify the linear, transition, and fully sliding regions. Determine the effective contact-patch length over which the tire bristles remain in the adhesion region. Compare brush model with the linear tire model.

Exemplars / Practical Applications

1. Full-vehicle simulation of a straight-line braking event using commercial multibody dynamics (MBD) software
2. Full-vehicle simulation of a straight-line acceleration event using commercial MBD software, with correlation of simulation results against experimental test data

Unit V	Lateral Dynamics	08 Hours

Introduction to vehicle lateral dynamics and cornering behavior, low-speed turning, tire cornering forces, bicycle-model formulation, understeer gradient, neutral steer, understeer and oversteer, critical and characteristic speeds, lateral acceleration gain, yaw-velocity gain, and vehicle sideslip angle, suspension effects on cornering, roll moment distribution, lateral force compliance steer, roll steer, aligning torque, lateral force versus camber angle, experimental determination of understeer characteristics using constant-radius and constant-speed methods, numerical examples and simulation of vehicle lateral dynamics using numerical computation or multibody dynamic analysis software.

Real World Assignment

1. Study the AIS and global standards related to double lane change, steep steer, steering assessment, roll, pitch and yaw measurements, and lane-change testing
2. Develop a 2-DOF bicycle model of a passenger car and investigate its lateral response during a constant-radius manoeuvre. Assume following parameters- vehicle mass, m in kg, yaw moment of inertia, I_z in kg·m², distance from CG to front axle, a in m, distance from CG to rear axle, b in m, front cornering stiffness, C_f N/rad, rear cornering stiffness C_r in N/rad, vehicle speed, V in m/s. Perform a constant-radius cornering simulation and determine the steering angle required to maintain a given radius turn at different vehicle speeds. Make other assumptions as appropriate.

Exemplars / Practical Applications

1. Correlation of subjective and objective ratings for ride and handling, i.e. test verses MBD simulations correlation
2. Tuning of the vehicle suspension to meet the customer comfort, regulatory requirements, and safety

Learning Resources

Text Books

1. Computer Aided Kinematics and Dynamics of Mechanical Systems- Vol. I: Basic Methods, E. J. Haug, Allyn and Bacon
2. Computer Aided Kinematics and Dynamics of Mechanical Systems- Vol. 2: Advanced Methods, E. J. Haug, Research Gate
3. Fundamentals of Vehicle Dynamics, T.D. Gillespie, Society of Automotive Engineers
4. Hans B. Pacejka, Tire and Vehicle Dynamics, Butterworth-Heinemann, Elsevier

Reference Books

1. Planar Multibody Dynamics: Formulation, Programming with MATLAB®, and Applications, P.E. Nikravesh, CRC Press
2. Dynamics of Multibody Systems, A.A. Shabana, Cambridge University Press
3. The Multibody Systems Approach to Vehicle Dynamics, M. Blundell and D. Harty, Butterworth-Heinemann/Elsevier
4. Reza N. Jazar, Vehicle Dynamics: Theory and Application, Springer

Web References

1. Prof. R. Krishnakumar, IIT, Madras, NPTEL Vehicle Dynamics Course https://nptel.ac.in/courses/107106080

Savitribai Phule Pune University
Final Year of Mechanical Engineering (2024 Pattern)

HVSE452MEC: Multibody Dynamics Lab

Teaching Scheme		Credit	Examination Scheme	
Theory	**NA**	**1**	**TW**	**25 Marks**
Practical	**2 Hours/Week**		**OR**	**25 Marks**

- **Prerequisite courses:**

Solid Mechanics, Design of Machine Elements, Dynamics of Machinery, Fundamentals of Machine Design and Optimization, Finite Element Analysis and Design of Experiments, Fundamentals of Low Frequency NVH and Automotive Applications, Multibody dynamics and vehicle dynamics

Course Objectives:

After completing this course, students will be able to:

1. **DEVELOP** multibody models of mechanical mechanisms and vehicle systems using rigid bodies, joints, constraints, and force elements
2. **APPLY** numerical and multibody dynamics methods for kinematic, dynamic, and inverse-dynamic analysis of mechanical systems
3. **ANALYSE** the effects of suspension, tyre, road, and steering inputs on vehicle ride and handling performance
4. **EVALUATE** mechanism and vehicle performance using appropriate simulation results, response measures, and engineering parameters
5. **APPLY** Design of experiments, optimization, and response surface methodology to improve mechanical and vehicle-system performance

Course Outcomes: After successful completion of the course, learner will be able to:

CO1: FORMULATE AND SOLVE kinematic constraint equations to determine the degrees of freedom, displacement, velocity, and acceleration of multibody systems

CO2: DEVELOP AND SIMULATE mechanism, quarter-car, half-car, and full-vehicle models using commercial MBD and numerical simulation tools

CO3: DETERMINE actuator forces, driving torques, and power requirements using dynamic and inverse-dynamic analyses

CO4: ASSESS vehicle ride, wheel-hop, pitch, and handling responses under representative road and steering maneuvers

CO5: OPTIMIZE mechanical and vehicle-system parameters using DoE, RSM, and numerical optimization subject to specified design and performance constraints

Guidelines for Conducting Laboratory Experiments

The student shall complete the following hands-on activities as a Term Work under the guidance of concerned faculty member. The open-source software shall be preferred for conducting practical sessions.

All experiments are compulsory

Experiment 1: Kinematic Analysis & DoE Study of a Quick Return Mechanism

For a quick-return mechanism, model each component as a rigid body and define the appropriate revolute, translational, and sliding joints and kinematic constraints. Determine the degrees of freedom by identifying the constraints imposed at each joint and expressing the constraints in terms of suitable generalized coordinates. Model the ground as a separate rigid body and prescribe the appropriate rotational driver for the input crank. Solve the resulting kinematic constraint equations, including the prescribed input motion, using Scilab, MATLAB, or an equivalent numerical solver to determine the displacement, velocity, and acceleration of the slider as functions of time. Determine the durations of the cutting and return strokes and calculate the corresponding quick-return ratio. Perform a Design of Experiments (DoE) study to identify the optimum combination of design parameters, subject to specified manufacturing, design, and packaging constraints, for achieving maximum cutting speed and minimum return-stroke time. Finally, optimize the quick-return ratio using numerical optimization and Response Surface Methodology (RSM), and evaluate the resulting optimum design against the specified performance requirements. Use Microsoft Excel, Scilab, or MATLAB or any other software for performing DOE study.

Exemplars / Practical Applications:

1. Designing a broaching machine
2. Designing a packaging machinery
3. Designing a lotting machine

Experiment 2: Inverse Dynamic Analysis of a Quick Return Mechanism

For the quick-return mechanism designed in Experiment 1, define the cutting force acting between the tool and workpiece as a function of slider position. Define the corresponding force–displacement relationship between the cutting force and the slider (x)-coordinate. Assume appropriate masses for all bodies and calculate their corresponding mass moments of inertia. Model the mechanism using numerical computation or multibody dynamic analysis software and perform an inverse dynamics analysis by prescribing a constant angular velocity for the input crank. Determine the driving torque required at the crank as a function of time and the crank angle over two complete crank rotations. Subsequently, incorporate a flywheel at the driver, i.e., at the motor location and investigate its effect on the motor torque requirement. Perform a Design of Experiments (DoE) study by varying the flywheel mass and moment of inertia, along with the motor parameters, to identify the optimum configuration that minimizes the peak motor torque while satisfying the specified operating conditions. Finally, plot and compare the driving torque as a function of crank angle for the configurations without and with the flywheel, and quantify the reduction in peak torque achieved through flywheel integration.

Exemplars / Practical Applications:

1. Industrial pick and place robot
2. Industrial cutting tools

Experiment 3: Perform Multibody Dynamic Analysis of Quarter Car Model

Develop and simulate a quarter-car model comprising sprung and unsprung masses, with the suspension and tyre represented by appropriate nonlinear spring and damper elements. Assume representative sprung and unsprung mass values based on a real-world passenger vehicle. Obtain the nonlinear load–deformation characteristics of a MacPherson strut and its damping characteristics during the compression and rebound strokes. Similarly, obtain representative tyre stiffness and damping properties from relevant literature. Perform multibody dynamic analyses of the quarter-car model for the following two road-input events:

For the rumble-road event, define a representative rubble road as a sinusoidal wave,

For the pothole event, define a representative pothole profile.

Simulate the vehicle for both events for various vehicle speeds. For both road-input events, determine and compare the displacement, velocity, and acceleration responses of the sprung and unsprung masses as functions of time. Evaluate the resulting ride frequency and wheel-hop behavior, and compare the vehicle response under the two road conditions for various speeds.

Exemplars / Practical Applications:

1. Performing kinematic and compliance & MBD analyses of a corner module
2. Performing kinematic and MBD analysis of a backhoe loader

Experiment 4: Perform Multibody Analysis of a Half Car Model

Develop and simulate a half-car model comprising sprung and unsprung masses. Represent the front and rear suspension systems using appropriate spring and damper elements, and model the front and rear tires using spring–damper elements with representative stiffness and damping characteristics. Obtain the nonlinear load–deformation characteristics of a MacPherson strut, together with its damping characteristics during the compression and rebound strokes. Similarly, obtain representative tyre stiffness and damping properties from relevant literature. Model the vehicle chassis as a rigid beam connecting the front and rear suspension hard points and define mass & inertial properties. Connect the front end of the chassis to the front suspension using a spherical (ball-and-socket) joint, and connect the rear end of the chassis to the rear suspension using revolute and translational joints. Perform multibody dynamic analyses of the half-car model for the following two road-input events: 1. For the rumble-road event, define a sinusoidal road profile, 2. For the pothole event, define a representative pothole profile. Simulate the vehicle passing through both the road surfaces at various speeds. For both events, determine the displacement, velocity, and acceleration of the sprung and unsprung masses as functions of time. Compare the front and rear suspension responses and evaluate the resulting vehicle ride and wheel-hop behavior under the two road conditions.

Exemplars / Practical Applications:

1. Performing kinematic and dynamic analysis of a truck
2. Performing kinematic and dynamic analysis of a fork lift

Experiment 5: Perform MBD Analysis of a Simplified Full car Model

Build a simplified full vehicle model for 4-wheeler, e.g., an intercollege competition vehicle such as Baja SAE, SUPRA SAE, Formula Bharat, or a model covered in section 12.5.1 of Reference 1, consisting of MacPherson strut suspension, torsion bars, chassis, steering rack, and the trailing arm. Simulate the vehicle traveling at a fixed initial velocity for the steering input- case 1: Lane change maneuver, and case 2: Constant radius simulations at three different speeds. Model the tire as a spring element with vertical stiffness and cornering stiffness C_α. Tire lateral force is generated by the lateral slip of the tire on the road surface and is approximated as $F_{lat} = C_\alpha \times \alpha$, where α is a slip angle. Lateral force cannot exceed $\mu \times F_{vertical}$. Define μ as the coefficient of friction between the tire and the road surface. The slip angle α is the angle between the tire heading and the velocity vector v, i.e., $\alpha = \psi - \psi_v$. Slip angle is the difference between the tire yaw angle ψ and the velocity angle ψ_v. Assume tire as vertical, i.e., without the caster, camber, and toe. Assume road surface as flat. Angle ψ is calculated from the definition of the Euler parameters of the spindle, presuming the tire is vertical; i.e., $\cos(\psi/2) = e_0$ and $\psi_v = -\tan^{-1}(v_x/v_y)$. Alternatively, you can use the tire models available in multibody dynamic analysis software. Determine the maximum safe speed for the lane change and constant radius simulations.

Exemplars / Practical Applications:

1. Correlation of an MBD model with experimental vehicle data for ride and handling evaluation
2. Road load data acquisition and correlation with a full vehicle MBD model

Learning Resources

Text Books

1. Computer Aided Kinematics and Dynamics of Mechanical Systems- Vol. I: Basic Methods, E. J. Haug, Allyn and Bacon
2. Computer Aided Kinematics and Dynamics of Mechanical Systems- Vol. 2: Advanced Methods, E. J. Haug, Research Gate
3. Fundamentals of Vehicle Dynamics, T.D. Gillespie, Society of Automotive Engineers
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4. Reza N. Jazar, Vehicle Dynamics: Theory and Application, Springer

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