جامعة طيبة
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Mechanical Engineering Department

ME 351: Mechanical Design I

Design of a 360 Degree Pendulum Ride

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ABSTRACT

This report presents a comprehensive mechanical design analysis of a 360° pendulum amusement ride, examining the structural loads, potential failure modes, and critical design considerations. The analysis focuses on the main structural components, including the support tower, pendulum arm, passenger gondola, pivot mechanism, and foundation system.

TABLE OF CONTENTS

1. INTRODUCTION

1.1 Ride Description

The 360° pendulum ride consists of a large rotating arm mounted on a central pivot point atop a support tower. The arm swings back and forth while simultaneously rotating, allowing the passenger gondola to complete full 360° revolutions. Typical specifications include:

- Arm length: 20-30 meters
- Tower height: 30-40 meters
- Passenger capacity: 30-50 riders
- Rotation speed: 10-15 RPM

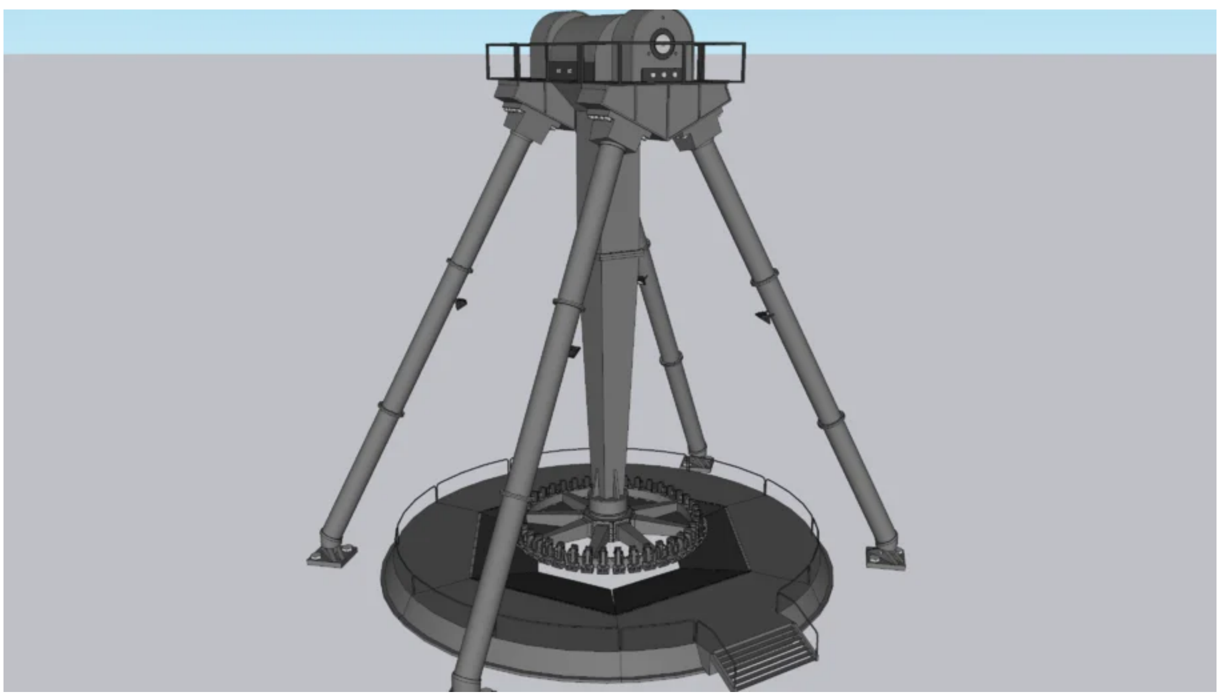

Figure 1 360 pendulum ride designed as CAD model shown the main parts

1.2 Design Objectives

- Ensure passenger safety under all operating conditions

- Withstand dynamic and cyclic loading
- Minimize fatigue failure risk
- Account for environmental factors (wind, temperature)
- Comply with engineering safety standards for amusement rides.

2. Load Analysis

2.1 Static Loads

Dead Loads:

- Structural self-weight of arm: 15,000-25,000 kg
- Gondola weight: 3,000-5,000 kg
- Passenger load: 50 passengers × 80 kg = 4,000 kg
- Drive mechanism and components: 2,000 kg
- Total static load ≈ 24,000-36,000 kg

$F_{grav} = (30{,}000)\ (9.81) = 294.3$ kN

2.2 Dynamic Loads

Centrifugal Force: At the gondola position during rotation:

$Fc = m \times \omega^2 \times r$

Where:

m = total mass at arm end

ω = angular velocity (rad/s)

r = arm radius

For a 25 m arm rotating at 12 RPM:

$\omega = 1.26$ rad/s

$F_c \approx 50{,}000$ N (varies with position)

Pendulum Swing Forces: Maximum acceleration at bottom of swing:

$a = v^2/r = (2\pi f \times r)^2 / r$

This generates forces of 19-29 N on the structure.

Gyroscopic Effects: The combination of swing and rotation creates complex gyroscopic moments that must be resisted by the pivot bearing system.

2.3 Environmental Loads

Wind Loading: Critical for tall structures. Using ASCE 7 standards:

$F = 0.5 \times \rho \times V^2 \times C_d \times A$

Where:

ρ = air density

V = wind velocity (design typically 90-120 km/h)

C_d = drag coefficient (1.2-2.0 for structural shapes)

A = projected area

Temperature Effects: Thermal expansion/contraction of steel members:

$\Delta L = \alpha \times L \times \Delta T$

Typical expansion: 12×10^{-6} /°C for steel

3. Critical Components Analysis

3.1 Pendulum Arm

Material: High-strength structural steel (ASTM A572 Grade 50 or higher)

Cross-section: Box or tubular section for torsional rigidity

Critical Stresses:

Bending Moment at the center point of the pendulum arm:

$M = F_{total} \times L$

Maximum stress: $\sigma = M \times c / I$

Combined Loading: Von Mises stress criterion:

$\sigma_{vm} = \sqrt{\sigma_x^2 + 3\tau_{xy}^2}$

Design Considerations:

- Factor of safety: 3-5 for ultimate strength
- Fatigue analysis for 10^7 cycles minimum
- Deflection limits: L/300 to prevent passenger discomfort

3.2 Central Pivot Bearing

Type: Large diameter slewing bearing with integrated gear ring

Design Requirements:

- Support combined radial, axial, and moment loads
- Bearing life: $L10 > 20{,}000$ operating hours
- Backlash control for smooth operation

Load Capacity Calculation:

$P = X \times Fr + Y \times Fa$

Where P = equivalent dynamic load, Fr = radial load, and Fa = axial load

Lubrication: Automatic grease system with load zone monitoring

3.3 Support Tower

Configuration: Lattice or tubular steel structure

Foundation Connection: Base plate with anchor bolts, moment-resisting connection

Buckling Analysis: Euler buckling for compression members:

$Pcr = \pi^2 \times E \times I / (K \times L)^2$

Where K = effective length factor

Lateral Stability: Must resist overturning moment:

$M\_overturning = F \times h$

Foundation must provide adequate resistance with safety factor ≥ 2.0

3.4 Drive System

Components:

Primary drive motor: 150-300 kW

Gearbox reduction: 50:1 to 100:1

Backup/emergency brake system

Clutch mechanism for controlled acceleration

Torque Requirements:

$T = I \times \alpha + T_{friction}$

Where I = moment of inertia, α = angular acceleration

3.5 Passenger Gondola

Structure: Tubular steel frame with restraint system mounting points

Restraint System:

Over-shoulder harnesses with redundant locking

Secondary backup restraints

Load testing at 3× maximum dynamic load

Stress Concentration: At restraint mounting points, use:

$\sigma_{max} = Kt \times \sigma_{nominal}$

Where Kt = stress concentration factor (typically 2-3 for holes/welds)

4. Failure Mode Analysis

4.1 Fatigue Failure

- High-Risk Locations:
- Weld joints at pivot connection
- Arm-to-gondola connection
- Bearing raceways

S-N Curve Analysis: For structural steel, fatigue limit ≈ 0.5 × ultimate tensile strength

Stress Range:

$\Delta\sigma = \sigma_{max} - \sigma_{min}$

Design Life: Using Miner's rule for cumulative damage:

$\Sigma(n_i/N_i) < 1$

Mitigation:

Smooth weld profiles, grinding to remove stress risers

Shot peening at critical locations

Regular NDT inspection (ultrasonic, dye penetrant)

4.2 Structural Overload

Scenarios:

- Emergency stop condition
- Component seizure during operation
- Extreme wind during operation

Load Factors:

- Operating loads: 1.5
- Emergency conditions: 2.0
- Proof load testing: 1.25 × design load

Critical Sections: Maximum bending at pivot point and arm mid-span

4.3 Bearing Failure

Failure Modes:

- Spalling of raceways
- Cage breakage
- Lubricant contamination
- Misalignment damage
- Preventive Measures
- Condition monitoring (vibration analysis, temperature)
- Regular lubrication per manufacturer schedule
- Seal integrity inspection
- Alignment verification

4.4 Connection Failures

Bolted Connections: Shear and tension in bolts:

$\tau = V / (n \times A)$

$\sigma = T / (n \times A)$

Preload: Minimum 70% of proof strength to prevent loosening

Weld Failures: Weld throat thickness design:

$t = F / (L \times \sigma_{allowable})$

4.5 Foundation Settlement

Differential Settlement: Allowable: < 1:500 over foundation width

Consequences:

Misalignment of pivot bearing

Increased stresses in tower

Vibration and noise issues

Monitoring:

Survey benchmarks

Tilt sensors

Regular alignment checks

5. Safety Systems

5.1 Redundancy

Critical Systems with Backup:

Dual braking systems (service and emergency)

Redundant restraint mechanisms

Backup power for controlled shutdown

Multiple position sensors

5.2 Emergency Stop

Deceleration Rate: Maximum 0.5g to prevent passenger injury

Braking Distance Calculation:

$d = v^2 / (2 \times a)$

Stopping Time: Typically, 5-10 seconds from full speed

5.3 Inspection and Maintenance

Daily:

Visual inspection of restraints and connections

Test emergency stop

Check hydraulic/pneumatic pressures

Weekly:

Bearing condition check

Lubrication inspection

Fastener torque verification

Monthly:

NDT of critical welds

Bearing vibration analysis

Structural alignment check

Annual:

Complete structural NDT

Load testing

Bearing replacement as needed

Third-party certification

6. Design Calculations Example

6.1 Arm Bending Stress

Given:

Arm length L = 25 m

End load (gondola + passengers) = 10,000 kg

Material: A572 Gr. 50 (Fy = 345 MPa)

Calculation:

Force $F = 10{,}000 \times 9.81 = 98{,}100$ N

Moment $M = F \times L = 98{,}100 \times 25 = 2{,}452{,}500$ N·m

For box section 600 mm × 600 mm × 20 mm:

$I = (600^4 - 560^4) / 12 = 2.59 \times 10^9 \text{ mm}^4$

$c = 300$ mm

$\sigma = M \times c / I = 2{,}452{,}500{,}000 \times 300 / 2.59 \times 10^9$

$\sigma = 284$ MPa

Safety Factor: SF = 345 / 284 = 1.22 (static only—needs dynamic analysis)

6.2 Bearing Selection

Load Components:

Radial load $F_r = 150$ kN

Axial load $F_a = 200$ kN

Moment $M = 3{,}000$ kN·m

Equivalent Load: For large slewing bearings, use the manufacturer's specific formula considering all load components.

Required Rating:

$C = P \times (L_{10h} \times n \times 60 / 10^6)^{(1/p)}$

Where p = 3 for ball bearings, 10/3 for roller bearings

7. Finite Element Analysis Recommendations

7.1 Model Setup

Elements:

- Shell elements for arm and tower
- Solid elements at connection details

- Beam elements for secondary members
- Mesh Refinement:
- Fine mesh at stress concentrations
- Weld toe regions
- Bearing contact areas

7.2 Load Cases

1. Maximum operational load with dynamics

2. Emergency stop condition

3. Wind load on stopped ride

4. Seismic loading

5. Combination cases per building codes

7.3 Analysis Types

- Static structural analysis
- Modal analysis for natural frequencies
- Harmonic response analysis
- Fatigue analysis with load history

8. Conclusions

The 360° pendulum ride presents significant mechanical design challenges due to:

1. **Complex Loading:** Combined bending, torsion, centrifugal, and gyroscopic effects
2. **Fatigue Concerns:** High cycle count requires careful detail design

3. **Safety Criticality:** Multiple redundant systems essential
4. **Scale:** Large forces and moments require robust structural design

Key Design Principles:

- Conservative factors of safety (3-5)
- Redundancy in all safety-critical systems
- Comprehensive inspection and maintenance program
- Quality fabrication and welding procedures
- Regular third-party certification
- Material Selection: High-strength low-alloy steels (HSLA) provide an optimal strength-to-weight ratio with good weldability and fatigue properties.

Future Improvements:

- Structural health monitoring systems
- Predictive maintenance using machine learning
- Advanced materials (high-strength composites)
- Active damping systems

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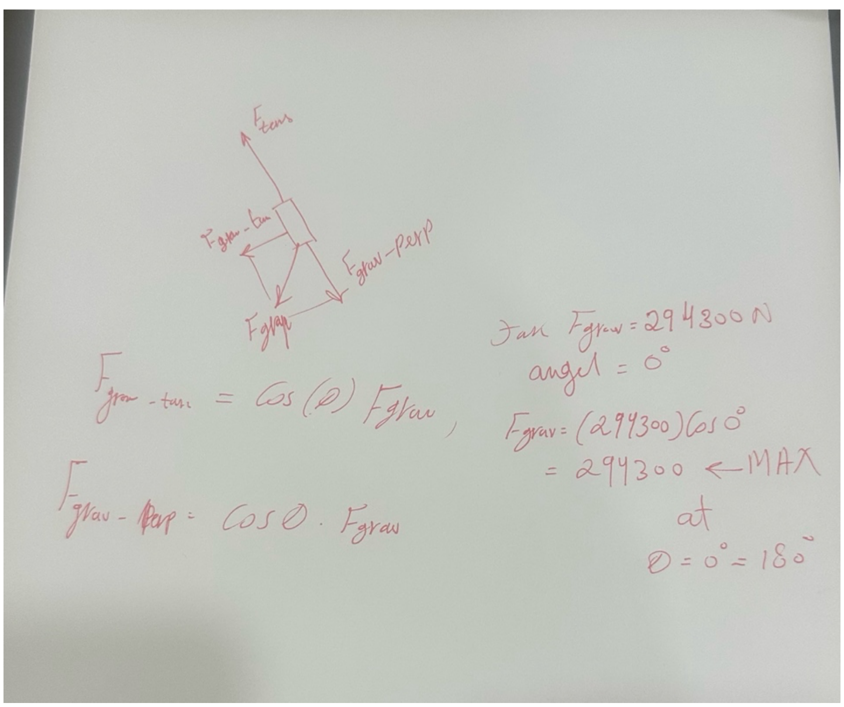
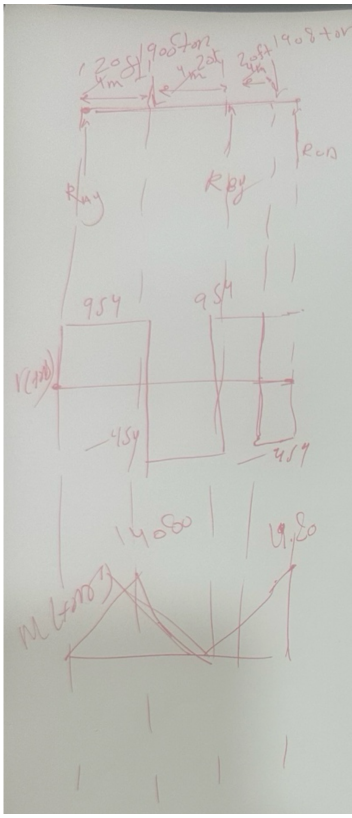
APPENDIX

Appendix A; handwritten calculation that used to calculate gravitation forces and MBD and SFD





$\Sigma X = 0 \quad \Sigma Y = 0$

$\Sigma M = 0$

$\Sigma Y = 0$

$\rightarrow = 1908 \text{ tons} + R_{Ay}$

$- 1908 \text{ tons} + R_{By}$

$+ R_{Cy}$

All in English unit

$\Sigma M_{RBy} = - 1908(20)$

$+ 2 R_x \, (40ft)$

$- 1908(20) \, ft$

$R_{By} - 1,908$