Innovation in Teaching Learning Process

Design of CD Nozzle using Python Code

Name of the Innovation	:	Design of convergent divergent Nozzle using Python code
Course Code and Name	:	High Speed Aerodynamics
Class and Semester	:	TY- Fifth semester
Academic Year and Term	:	2024-2025, ODD
Faculty Name and Designation	:	Kaleeswaran Periyasamy, Assistant Professor

Introduction:

A convergent-divergent (C-D) nozzle, also known as a de Laval nozzle, is a specially shaped nozzle designed to accelerate fluid to supersonic speeds. It is widely used in rocket propulsion, jet engines, and industrial applications where high-velocity gas flow is required.

The C-D nozzle consists of three main sections:

- Convergent Section: Compresses the flow, increasing velocity as it approaches the throat.
- Throat: The narrowest section, where the velocity reaches sonic speed (Mach 1).
- Divergent Section: Expands the flow, accelerating it further to supersonic speeds.

Conventional designs may generate shock waves within the divergent section, leading to energy loss.

The Method of Characteristics (MOC) ensures smooth expansion, eliminating undesired shock waves inside the nozzle.

1. Eliminating Shock-Induced Losses

   Conventional designs may generate shock waves within the divergent section, leading to energy loss.The Method of Characteristics (MOC) ensures smooth expansion, eliminating undesired shock waves inside the nozzle.

2. Optimizing Nozzle Length

   Traditional nozzles tend to be longer than necessary, increasing weight and material costs.The Minimum Length Nozzle Design determines the shortest possible nozzle shape that achieves desired supersonic flow efficiently.

3. Enhancing Thrust and Propulsion Efficiency

   A well-designed C-D nozzle maximizes thrust efficiency by ensuring proper flow expansion.Using innovative techniques helps in designing adaptive nozzles that work efficiently in varying atmospheric conditions (e.g., altitude adaptability in rockets).

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4. Reducing Flow Separation Risks

   Over-expanded flow in poorly designed nozzles can cause boundary layer separation, leading to performance loss. MOC-based nozzle contours provide a gradual expansion path, reducing the likelihood of separation.

5. Application in Next-Gen Aerospace and Hypersonic Vehicles

   Future spacecraft and hypersonic propulsion systems require highly efficient nozzles for fuel savings and performance optimization.MOC-based nozzles can be integrated with adaptive and aerospike nozzles for next-generation propulsion systems.

Motivation/Purpose of Innovative Technique:

The design of Convergent-Divergent (C-D) nozzles plays a crucial role in aerospace propulsion, jet engines, and industrial applications where achieving efficient supersonic flow is essential. Traditional nozzle designs often face challenges like shock wave formation, flow separation, and inefficiencies at varying operating conditions. To overcome these, innovative techniques like the Method of Characteristics (MOC) and Minimum Length Nozzle Design.

✅ Achieve a shock-free expansion process to maximize nozzle efficiency.

✅ Reduce nozzle length without compromising performance.

✅ Improve thrust effectiveness by designing an optimized exit Mach number.

✅ Ensure adaptability to various operating conditions.

Procedure Followed:

Process Involved in the Design of a Convergent-Divergent (C-D) Nozzle Using the Method of Characteristics and Minimum Length Nozzle

The design of a C-D nozzle involves determining the nozzle contour that ensures gradual expansion and acceleration of the flow to supersonic velocities without shock formation. Two key approaches are used:

1. Method of Characteristics (MOC) – Provides a mathematical technique to design a smooth, shock-free expansion contour.
2. Minimum Length Nozzle – Ensures the shortest nozzle length required to achieve supersonic flow.

1. Method of Characteristics (MOC) for C-D Nozzle Design

The Method of Characteristics is used to design a smooth, shock-free nozzle by solving the governing equations of compressible, inviscid flow.

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Steps in MOC for Nozzle Design:

1. Define Input Conditions:
   - Stagnation pressure (P0 and temperature (T0).
   - Throat conditions where the flow reaches Mach 1.
2. Isentropic Expansion:
   - The nozzle expands the flow from Mach 1 at the throat to a desired exit Mach number.
   - The Prandtl-Meyer function (ν) governs this expansion:
   - The maximum expansion angle θ_{max}
3. Characteristic Lines and Grid Construction:
   - The nozzle is divided into small characteristic regions, where expansion waves propagate.
   - Using compatibility equations, expansion lines and Mach waves are computed using:
     $\theta+\nu$ =constant (C+ wave) $\theta-\nu$=constant (C- wave)
4. Numerical Integration and Contour Calculation:
   - By solving characteristic equations at each expansion point, the contour shape is determined.
   - The final nozzle wall contour is obtained by smoothly connecting these expansion waves.

2. Minimum Length Nozzle Design

The minimum length nozzle is the shortest possible nozzle that expands the flow without shocks. It follows these principles:

Steps in Minimum Length Nozzle Design:

1. Initial Expansion at Throat:
   - Flow starts at Mach 1 at the throat.
   - A small expansion fan initiates at the throat, creating a Prandtl-Meyer expansion region.
2. Expansion Wave Propagation:
   - Expansion waves propagate outward from the throat region.
   - The flow gradually expands without discontinuities.
3. Formation of Nozzle Contour:
   - The shape of the nozzle is determined using MOC-derived expansion angles.
   - The nozzle wall curvature smoothly follows the last expansion wave.
4. Final Exit Conditions:
   - The exit Mach number, pressure, and temperature match the required design conditions.
   - This ensures an efficient expansion process with minimum length and no shock losses.

Sample Python Code:

```
import numpy as np

 import matplotlib.pyplot as plt

 import pandas as pd

 # Constants

 gamma = 1.4 #Specific heat ratio for air
```

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```
offset_y = 0.5 # Offset in meters for the y-direction at the start
# Prandtl-Meyer function
def prandtl_meyer(M):
return np.sqrt((gamma + 1) / (gamma- 1)) * np.arctan(np.sqrt((M**2- 1) * (gamma- 1) / (gamma +
1)))- np.arctan(np.sqrt(M**2- 1))
# Mach expansion angle calculation
def mach_expansion(M_exit, M_throat):
return prandtl_meyer(M_exit)- prandtl_meyer(M_throat)
# Generate the nozzle contour
def generate_nozzle_contour(M_exit, M_throat, num_points=100):
x =np.linspace(0, 1, num_points) * 1000 # Axial distance in mm
y =np.zeros(num_points) # Initialize contour in meters
# Flow angles based on characteristics
flow_angle = mach_expansion(M_exit, M_throat) / num_points
for i in range(1, num_points):
y[i] = y[i- 1] + np.tan(flow_angle * (i / num_points))
# Adjust for offset and convert to mm
y =(y +offset_y) * 1000
return x, y
# Define exit Mach number and throat conditions
M_throat = 1.0
M_exit = 2.8 # Updated for a final exit Mach of 3
# Generate nozzle contour
x, y = generate_nozzle_contour(M_exit, M_throat)
# Print the list of coordinates for the CD nozzle
coordinates = list(zip(x, y))
```

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```
print("List of CD Nozzle Coordinates (Axial Position, Nozzle Radius):")

for coord in coordinates:

print(f"({coord[0]:.1f} mm, {coord[1]:.1f} mm)")

# Plot the nozzle contour

plt.figure(figsize=(10, 5))

plt.plot(x, y, label='Nozzle Contour')

plt.scatter(x, y, color='red', s=10) # Mark points with small red dots

# Finalize plot

plt.title(f'Supersonic Nozzle Contour with Offset (M_exit={M_exit})')

plt.xlabel('Axial Position (mm)')

plt.ylabel('Nozzle Radius (mm)')

plt.grid()

plt.axis('equal')

plt.legend()

plt.show()

# Save the contour data to a CSV file (compatible with Google Sheets)

df = pd.DataFrame({'Axial Position (mm)': x, 'Nozzle Radius (mm)': y})

df.to_csv('nozzle_contour_with_offset.csv', index=False)

print("Nozzle contour data with offset has been saved to 'nozzle_contour_with_offset.csv'.")
```

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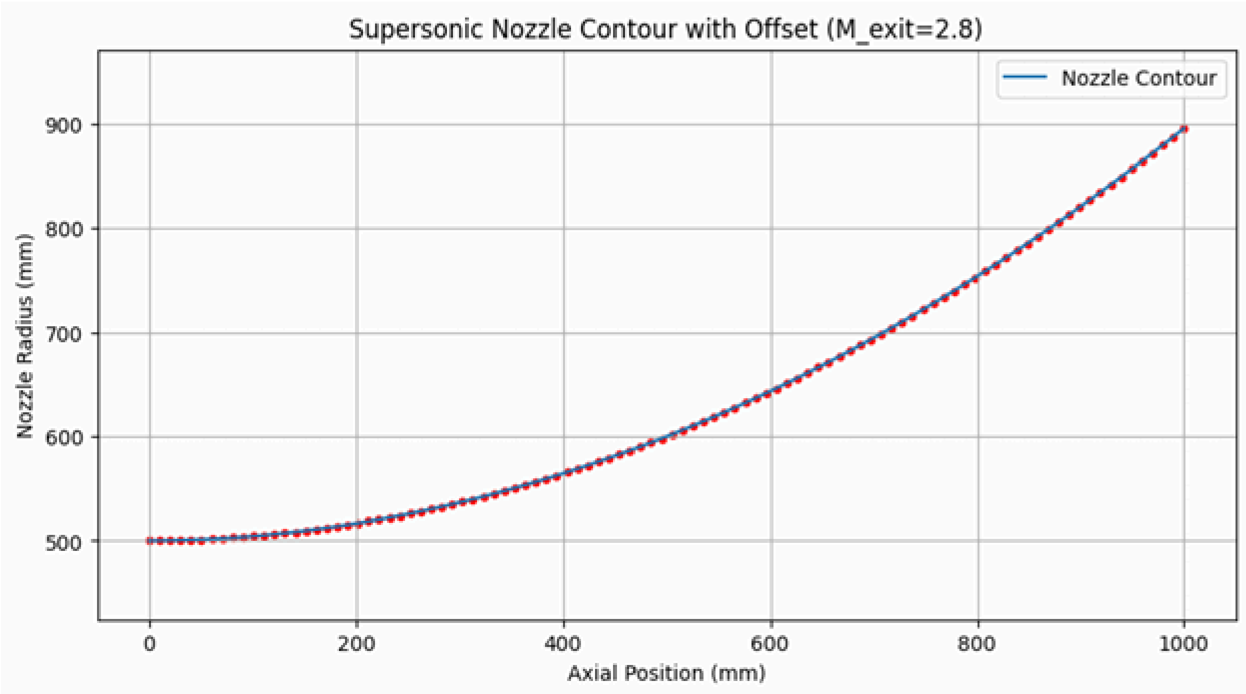

Outcome:

- Design CD nozzles to the application of the supersonic flow, and calculate lift and drag on flat plate wings at transonic speeds.
- Interpret & Analyse the upstream and downstream flow behaviour by calculating the flow field parameters using shock wave or expansion waves relations applicable to high speed compressible flows.
- Demonstrate a comprehensive understanding of fundamental equations and concepts in high-speed aerodynamics to apply these equations and concepts to solve a range of aerodynamic problems, including those involving isentropic one-dimensional flow and compressible flows.

A smooth, shock-free nozzle shape is obtained, ensuring efficient supersonic expansion.The expansion angle and wall curvature are optimized for uniform flow acceleration.Supersonic Flow Achieved at the Nozzle Exit. The designed nozzle ensures a gradual increase in Mach number from Mach 1 at the throat to the desired exit Mach number. The expansion process occurs isentropically, minimizing losses. Prevention of Shock Waves and Flow Separation.Proper nozzle contouring avoids shock formation, ensuring efficient thrust production. Flow separation is minimized, leading to higher propulsion efficiency. Minimum Length Requirement Met. The nozzle is designed with the shortest possible length that achieves the desired supersonic expansion.The nozzle provides maximum thrust efficiency by ensuring proper exhaust expansion. Used in rocket engines, jet propulsion, and industrial gas dynamics applications.

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3. Modern Compressible Flow with Historical Perspective, John D Anderson ,McGraw-Hill Publications, 2003