

# Nonlinear Systems in Two Dimensions

Two-Term Linearization in  $x$  and  $y$

MMAE 450

# Nonlinear Systems of Equations

Many engineering problems lead to systems of nonlinear equations:

$$\mathbf{F}(\mathbf{x}) = \mathbf{0}, \quad \mathbf{x} = \begin{bmatrix} x \\ y \end{bmatrix}.$$

Examples include:

- ▶ nonlinear material behavior,
- ▶ geometric nonlinearity,
- ▶ nonlinear boundary conditions.

To solve these systems, we rely on *local linearization*.

## A Two-Dimensional Nonlinear System

Consider a system of two nonlinear equations:

$$\begin{aligned}F_1(x, y) &= 0, \\F_2(x, y) &= 0.\end{aligned}$$

We seek a solution  $(x, y)$  that satisfies both equations simultaneously.

In general, these equations cannot be solved analytically.

## Local Linearization About a Point

Let  $(x_0, y_0)$  be a current approximation to the solution.

We approximate the nonlinear system near this point using a first-order Taylor expansion.

This is a direct generalization of the 1D Taylor expansion.

## Two-Term Taylor Expansion (2D)

Each component of  $\mathbf{F}$  is expanded about  $(x_0, y_0)$ :

$$F_1(x, y) \approx F_1(x_0, y_0) + \frac{\partial F_1}{\partial x}(x_0, y_0)(x - x_0) + \frac{\partial F_1}{\partial y}(x_0, y_0)(y - y_0),$$

$$F_2(x, y) \approx F_2(x_0, y_0) + \frac{\partial F_2}{\partial x}(x_0, y_0)(x - x_0) + \frac{\partial F_2}{\partial y}(x_0, y_0)(y - y_0).$$

Higher-order terms are neglected.

## Linearized System in Matrix Form

The linearized system can be written compactly as:

$$\mathbf{F}(x, y) \approx \mathbf{F}(x_0, y_0) + \mathbf{J}(x_0, y_0) \begin{bmatrix} x - x_0 \\ y - y_0 \end{bmatrix},$$

where  $\mathbf{J}$  is the Jacobian matrix:

$$\mathbf{J} = \begin{bmatrix} \frac{\partial F_1}{\partial x} & \frac{\partial F_1}{\partial y} \\ \frac{\partial F_2}{\partial x} & \frac{\partial F_2}{\partial y} \end{bmatrix}.$$

## What Does the Jacobian Represent?

- ▶ The Jacobian generalizes the concept of a derivative to multiple dimensions
- ▶ It describes how the system changes with respect to small changes in  $(x, y)$
- ▶ It provides the best linear approximation near the current point

### Key Idea

Nonlinear problems are solved by repeatedly solving linearized systems.

## Why Linearization Matters

- ▶ Enables iterative solution methods (Newton-type methods)
- ▶ Converts nonlinear problems into a sequence of linear solves
- ▶ Forms the foundation of nonlinear finite element analysis

### Looking Ahead

Next, we will use this linearization to construct Newton's method for solving nonlinear systems.