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Part I

Multivariable Calculus

Chapter 11

Parametric Equations and Polar Coordinates

11.1 Curves Defined by Parametric Equations

Suppose that x and y are both given as functions of a third variable t (called a **parameter** by the equations)

$$x = f(t) \quad y = g(t)$$

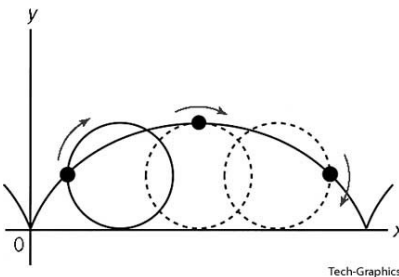
(called **parametric equations**). Each value of t determines a point (x,y) . As t changes, $(x,y) = (f(t), g(t))$ changes and traces out a curve C , which is called a **parametric curve**. The direction of the arrows on curve C show the change in the position of the equation as t increases.

We can also restrict t to a finite interval. In general, the curve with parametric equations

$$x = f(t) \quad y = g(t) \quad a \leq t \leq b$$

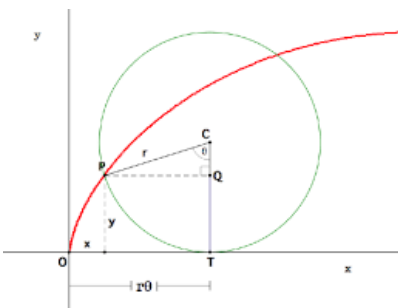
has **initial point** $(f(a), g(a))$ and **terminal point** $(f(b), g(b))$.

The Cycloid



Example 11.1.1. A circle with radius r rolls along the x -axis. The curve traced out by a point P on the circumference of the circle is called a **cycloid**. Find parametric equations for the cycloid.

Solution. We will use the angle of rotation θ as the parameter ($\theta = 0$ when P is at the origin).



Suppose the circle has rotated θ radians. Using the figure, the distance it has rolled from the origin is

$$|OT| = \text{arc } PT = r\theta$$

because P starts at the origin. Therefore, the center of the circle is $C(r\theta, r)$. Let the coordinates of P be (x, y) . Then from the figure,

$$x = |OT| - |PQ| = r\theta - r\sin\theta = r(\theta - \sin\theta)$$

$$y = |TC| - |QC| = r - r\cos\theta = r(1 - \cos\theta)$$

Definition 11.1.1. Parametric equations of the cycloid are

$$x = r(\theta - \sin\theta) \quad y = r(1 - \cos\theta)$$

11.2 Calculus with Parametric Curves

We will mainly solve problems involving tangents, area, arc length, and surface area.

Tangents

In the previous section, we saw that some curves defined by parametric equations $x = f(t)$ and $y = g(t)$ can also be expressed, by eliminating the parameter, in the form $y = F(x)$. If we substitute $x = f(t)$ and $y = g(t)$ in the equation $y = F(x)$, we get

$$g(t) = F(f(t))$$

If g , f , and F are differentiable, the Chain Rule gives

$$g'(t) = F'(f(t))f'(t) = F'(x)f'(t)$$

If $f'(t) \neq 0$, we can solve for $F'(x)$:

Definition 11.2.1. The slope of the tangent to the parametric curve $y = F(x)$ is $F'(x)$.

$$F'(x) = \frac{g'(t)}{f'(t)}$$

This enables us to find tangents to parametric curves without having to eliminate the parameter. We can rewrite the previous equation in an easily remembered form.

Definition 11.2.2. We can use this to find tangents to parametric curves without having to eliminate the parameter.

$$\frac{dy}{dx} = \frac{\frac{dy}{dt}}{\frac{dx}{dt}} \quad \text{if} \quad \frac{dx}{dt} \neq 0$$

The curve has a

- horizontal tangent when $\frac{dy}{dt} = 0$ (provided that $\frac{dx}{dt} \neq 0$)
- vertical tangent when $\frac{dx}{dt} = 0$ (provided that $\frac{dy}{dt} \neq 0$)

This is useful when sketching parametric curves.

Definition 11.2.3. We can also find $\frac{d^2y}{dx^2}$

$$\frac{d^2y}{dx^2} = \frac{d}{dx} \left(\frac{dy}{dx} \right) = \frac{\frac{d}{dt} \left(\frac{dy}{dx} \right)}{\frac{dx}{dt}}$$

Example 11.2.1. A curve C is defined by the parametric equations $x = t^2$, $y = t^3 - 3t$.

1. Show that C has two tangents at the point (3,0) and find their equations.
2. Find the points on C where the tangent is horizontal or vertical.
3. Determine where the curve is concave upward or downward.

Solution. A curve C is defined by the parametric equations $x = t^2$, $y = t^3 - 3t$.

1. Rewrite $y = t^3 - 3t = t(t^2 - 3) = 0$ when $t = 0$ or $t = \pm\sqrt{3}$. This indicates that C intersects itself at (3,0).

$$\frac{dy}{dx} = \frac{dy/dt}{dx/dt} = \frac{3t^2 - 3}{2t} = \frac{3}{2} \left(t - \frac{1}{t} \right)$$

$$t = \pm\sqrt{3} \rightarrow dy/dx = \pm 6/(2\sqrt{3})$$

so the equations of the tangents at (3,0) are

$$y = \sqrt{3}(x - 3) \quad \text{and} \quad y = -\sqrt{3}(x - 3)$$

2. C has a horizontal tangent when $dy/dx = 0$. In other words, when $dy/dt = 0$ and $dx/dt \neq 0$. $dy/dt = 3t^2 - 3 = 0$ when $t^2 = 1$ so $t = \pm 1$. This means there are horizontal tangents on C at $(1, -2)$ and $(-1, 2)$. C has a vertical tangent when $dx/dt = 2t = 0$, so $t = 0$. This means C has a vertical tangent at $(0, 0)$.
3. To determine concavity we calculate the second derivative:

$$\frac{d^2y}{dx^2} = \frac{\frac{d}{dt}\left(\frac{dy}{dx}\right)}{\frac{dx}{dt}} = \frac{\frac{3}{2}\left(1 + \frac{1}{t^2}\right)}{2t} = \frac{3(t^2 + 1)}{4t^3}$$

The curve is concave upward when $t > 0$ and concave downward when $t < 0$.

Area

We already know that area under a curve $y = F(x)$ from a to b is $A = \int_a^b F(x)dx$. We can apply this to parametric equations using the Substitution Rule for Definite Integrals.

Definition 11.2.4. If the curve C is given by parametric equations $x = f(t)$ and $y = g(t)$ and t increases from α to β ,

$$A = \int_a^b ydx = \int_\alpha^\beta g(t)f'(t)dt$$

(Switch α to β if the point on C at β is more left than α .)

Example 11.2.2. Find the area under one arch of the cycloid $x = r(\theta - \sin \theta)$, $y = r(1 - \cos \theta)$.

Solution. One arch of the cycloid is given by $0 \leq \theta \leq 2\pi$. Using the Substitution Rule with $y = r(1 - \cos \theta)$ and $dx = r(1 - \cos \theta)d\theta$, we have

$$\begin{aligned} A &= \int_0^{2\pi} ydx = \int_0^{2\pi} r(1 - \cos \theta)r(1 - \cos \theta)d\theta \\ &= r^2 \int_0^{2\pi} (1 - \cos \theta)^2 d\theta = r^2 \int_0^{2\pi} (1 - 2\cos \theta + \cos^2 \theta) d\theta \\ &= r^2 \int_0^{2\pi} \left[1 - 2\cos \theta + \frac{1}{2}(1 + \cos 2\theta) \right] d\theta \\ &= r^2 \left[\frac{3}{2}\theta - 2\sin \theta + \frac{1}{4}\sin 2\theta \right]_0^{2\pi} \\ &= r^2 \left(\frac{3}{2} \cdot 2\pi \right) = 3\pi r^2 \end{aligned}$$

Arc Length

Surface Area

11.3 Polar Coordinates

11.4 Areas and Lengths in Polar Coordinates

11.5 Conic Sections

11.6 Conic Sections in Polar Coordinates

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18.3 Applications of Second-Order Differential Equations

18.4 Series Solutions