10.6.1

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Question

Draw a circle of radius 2.5cm. Take a point P outside the circle at a distance of 7cm from the center. Then construct a pair of tangents to the circle from point P.

Theoretical Solution

The tangent directions $\mathbf{m}$ from an external point $\mathbf{h}$ to the circle $g(\mathbf{x}) = \mathbf{x}^\top \mathbf{x} - r^2 = 0$ satisfy $\mathbf{m}^\top \boldsymbol{\Sigma} \mathbf{m} = 0$, where

$$\boldsymbol{\Sigma} = \mathbf{h}\mathbf{h}^\top - g(\mathbf{h})\,\mathbf{I} \tag{1}$$

With the point $\mathbf{h} = d\mathbf{e_1}$, we have $g(\mathbf{h}) = d^2 - r^2$. From (1),

$$\begin{aligned} \boldsymbol{\Sigma} &= \begin{pmatrix} d^2 & 0 \\ 0 & 0 \end{pmatrix} - \begin{pmatrix} d^2 - r^2 & 0 \\ 0 & d^2 - r^2 \end{pmatrix} \\ &= \begin{pmatrix} r^2 & 0 \\ 0 & -\left(d^2 - r^2\right) \end{pmatrix} \end{aligned} \tag{2}$$

Theoretical Solution

Since $\boldsymbol{\Sigma}$ is a diagonal matrix, its eigenvalues are the diagonal entries.

$$\lambda_1 = r^2,\ \lambda_2 = -\left(d^2 - r^2\right) \tag{3}$$

The matrix of orthonormal eigenvectors is

$$\mathbf{P} = \mathbf{I} \tag{4}$$

The unit direction vectors of the tangents are given by the formula:

$$\mathbf{m} = \frac{1}{\sqrt{\lambda_1 - \lambda_2}}\mathbf{P}\begin{pmatrix} \sqrt{-\lambda_2} \\ \pm\sqrt{\lambda_1} \end{pmatrix} \tag{5}$$

Theoretical Solution

We calculate the terms for (5):

$$\lambda_1 - \lambda_2 = r^2 - \left(-\left(d^2 - r^2\right)\right) = d^2 \tag{6}$$

$$-\lambda_2 = d^2 - r^2 \tag{7}$$

Substituting these into (5):

$$\mathbf{m} = \frac{1}{\sqrt{d^2}}\mathbf{I}\begin{pmatrix} \sqrt{d^2 - r^2} \\ \pm\sqrt{r^2} \end{pmatrix} = \frac{1}{d}\begin{pmatrix} \sqrt{d^2 - r^2} \\ \pm r \end{pmatrix} \tag{8}$$

Theoretical Solution

The points of contact are $\mathbf{q} = \mathbf{h} + \kappa\mathbf{m}$. The parameter κ is found by substituting the line equation into the circle equation:

$$g\left(\mathbf{h} + \kappa\mathbf{m}\right) = \left(\mathbf{h} + \kappa\mathbf{m}\right)^\top \left(\mathbf{h} + \kappa\mathbf{m}\right) - r^2 = 0 \tag{9}$$

$$\kappa^2 \left(\mathbf{m}^\top \mathbf{m}\right) + 2\kappa \left(\mathbf{h}^\top \mathbf{m}\right) + g\left(\mathbf{h}\right) = 0 \tag{10}$$

For a tangent, this quadratic has a single repeated root.

Theoretical Solution

Since $\mathbf{m}$ is a unit vector, the value of κ for the point of contact is:

$$\kappa = \frac{-2\left(\mathbf{h}^\top \mathbf{m}\right)}{2\left(1\right)} = -\mathbf{h}^\top \mathbf{m} \tag{11}$$

We require $\kappa < 0$, which implies $\mathbf{h}^\top \mathbf{m} > 0$.

$$\mathbf{h}^\top \mathbf{m} = \left(d\mathbf{e_1}\right)^\top \frac{1}{d}\begin{pmatrix}\sqrt{d^2 - r^2} \\ \pm r\end{pmatrix} = \sqrt{d^2 - r^2} > 0 \tag{12}$$

The condition is satisfied, and so $\kappa = -\sqrt{d^2 - r^2}$.

The points of contact are $\mathbf{q} = \mathbf{h} + \kappa\mathbf{m}$.

$$\begin{aligned}\mathbf{q} &= d\mathbf{e_1} - \sqrt{d^2 - r^2}\left(\frac{1}{d}\begin{pmatrix}\sqrt{d^2 - r^2} \\ \pm r\end{pmatrix}\right) \\ &= \begin{pmatrix} d \\ 0 \end{pmatrix} - \begin{pmatrix} \frac{d^2-r^2}{d} \\ \pm\frac{r\sqrt{d^2-r^2}}{d} \end{pmatrix} \\ &= \begin{pmatrix} \frac{r^2}{d} \\ \mp\frac{r\sqrt{d^2-r^2}}{d} \end{pmatrix}\end{aligned} \tag{13}$$

Final Calculation

Substituting $r = 2.5$ and $d = 7$:

$$\mathbf{q} = \begin{pmatrix} \frac{(2.5)^2}{7} \\ \pm\frac{2.5\sqrt{7^2-(2.5)^2}}{7} \end{pmatrix} = \begin{pmatrix} \frac{6.25}{7} \\ \pm\frac{2.5\sqrt{42.75}}{7} \end{pmatrix} = \begin{pmatrix} \frac{25}{28} \\ \pm\frac{2.5\sqrt{42.75}}{7} \end{pmatrix} \tag{14}$$

Plot

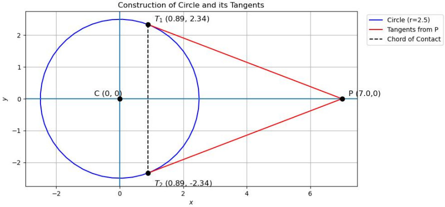

Figure: Plot