Problem 12

In each of Problems 5 through 12, find the general solution of the given differential equation. In Problems 11 and 12, g is an arbitrary continuous function.

$$y'' + 4y = g(t)$$

Solution

Because this ODE is linear, the general solution can be expressed as a sum of the complementary solution $y_c(t)$ and the particular solution $y_p(t)$.

$$y(t) = y_c(t) + y_p(t)$$

The complementary solution satisfies the associated homogeneous equation.

$$y_c'' + 4y_c = 0 \tag{1}$$

This is a homogeneous ODE with constant coefficients, so the solution is of the form $y_c = e^{rt}$.

$$y_c = e^{rt} \quad \rightarrow \quad y_c' = re^{rt} \quad \rightarrow \quad y_c'' = r^2 e^{rt}$$

Substitute these expressions into the ODE.

$$r^2 e^{rt} + 4(e^{rt}) = 0$$

Divide both sides by e^{rt}.

$$r^2 + 4 = 0$$

$$r = \{-2i, 2i\}$$

Two solutions to equation (1) are then $y_c = e^{-2it}$ and $y_c = e^{2it}$. By the principle of superposition, the general solution is a linear combination of these two.

$$\begin{aligned} y_c(t) &= C_1 e^{-2it} + C_2 e^{2it} \\ &= C_1[\cos(-2t) + i\sin(-2t)] + C_2[\cos(2t) + i\sin(2t)] \\ &= C_1[\cos(2t) - i\sin(2t)] + C_2[\cos(2t) + i\sin(2t)] \\ &= C_1 \cos 2t - iC_1 \sin 2t + C_2 \cos 2t + iC_2 \sin 2t \\ &= (C_1 + C_2)\cos 2t + (-iC_1 + iC_2)\sin 2t \\ &= C_3 \cos 2t + C_4 \sin 2t \end{aligned}$$

According to the method of variation of parameters, the particular solution is obtained by allowing the parameters in $y_c(t)$ to vary.

$$y_p(t) = C_3(t)\cos 2t + C_4(t)\sin 2t$$

It satisfies the following ODE.

$$y_p'' + 4y_p = g(t)$$

Substitute the previous formula in for $y_p(t)$.

$$[C_3(t)\cos 2t + C_4(t)\sin 2t]'' + 4[C_3(t)\cos 2t + C_4(t)\sin 2t] = g(t)$$

Evaluate the derivatives.

$$[C_3'(t)\cos 2t - 2C_3(t)\sin 2t + C_4'(t)\sin 2t + 2C_4(t)\cos 2t]' + 4[C_3(t)\cos 2t + C_4(t)\sin 2t] = g(t)$$

$$[C_3''(t)\cos 2t - 2C_3'(t)\sin 2t - 2C_3'(t)\sin 2t - \cancel{4C_3(t)\cos 2t} + C_4''(t)\sin 2t + 2C_4'(t)\cos 2t + 2C_4'(t)\cos 2t - \cancel{4C_4(t)\sin 2t}] + \cancel{4C_3(t)\cos 2t} + \cancel{4C_4(t)\sin 2t} = g(t)$$

$$C_3''(t)\cos 2t - 4C_3'(t)\sin 2t + C_4''(t)\sin 2t + 4C_4'(t)\cos 2t = g(t)$$

If we set

$$C_3''(t)\cos 2t - 4C_3'(t)\sin 2t = 0, \tag{2}$$

then the previous equation reduces to

$$C_4''(t)\sin 2t + 4C_4'(t)\cos 2t = g(t). \tag{3}$$

The aim now is to solve this system of two equations for $C_3(t)$ and $C_4(t)$. Start by dividing equation (2) by $\cos 2t$.

$$C_3''(t) - 4\frac{\sin 2t}{\cos 2t}C_3'(t) = 0$$

Use an integrating factor I_1 to solve it.

$$I_1 = \exp\left(\int^t -4\frac{\sin 2s}{\cos 2s}\,ds\right) = e^{2\ln\cos 2t} = e^{\ln\cos^2 2t} = \cos^2 2t$$

Multiply both sides of the previous equation by I_1.

$$(\cos^2 2t)C_3''(t) - (4\sin 2t\cos 2t)C_3'(t) = 0$$

The left side can be written as $d/dt[I_1 C_3'(t)]$ by the product rule.

$$\frac{d}{dt}[(\cos^2 2t)C_3'(t)] = 0$$

Integrate both sides with respect to t, setting the integration constant to zero.

$$(\cos^2 2t)C_3'(t) = 0$$

Divide both sides by $\cos^2 2t$.

$$C_3'(t) = 0$$

Integrate both sides with respect to t once more, setting the integration constant to zero.

$$C_3(t) = 0$$

Divide both sides of equation (3) by $\sin 2t$.

$$C_4''(t) + 4\frac{\cos 2t}{\sin 2t}C_4'(t) = \frac{g(t)}{\sin 2t}$$

Use an integrating factor I_2 to solve it.

$$I_2 = \exp\left(\int^t 4\frac{\cos 2s}{\sin 2s}\,ds\right) = e^{2\ln\sin 2t} = e^{\ln\sin^2 2t} = \sin^2 2t$$

Multiply both sides of the previous equation by I_2.

$$(\sin^2 2t)C_4''(t) + (4\cos 2t \sin 2t)C_4'(t) = g(t)\sin 2t.$$

The left side can be written as $d/dt[I_2 C_4'(t)]$ by the product rule.

$$\frac{d}{dt}[(\sin^2 2t)C_4'(t)] = g(t)\sin 2t$$

Integrate both sides with respect to t, setting the integration constant to zero.

$$(\sin^2 2t)C_4'(t) = \int^t g(s)\sin 2s\, ds$$

Divide both sides by $\sin^2 2t$.

$$C_4'(t) = \csc^2 2t \int^t g(s)\sin 2s\, ds$$

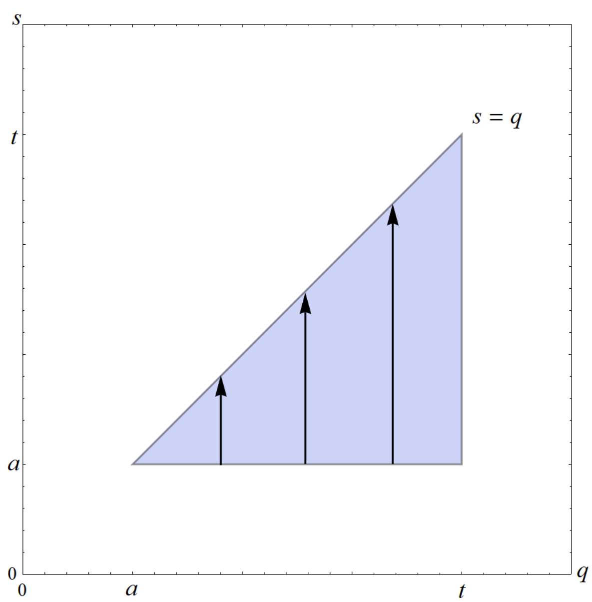
Integrate both sides with respect to t once more, setting the integration constant to zero.

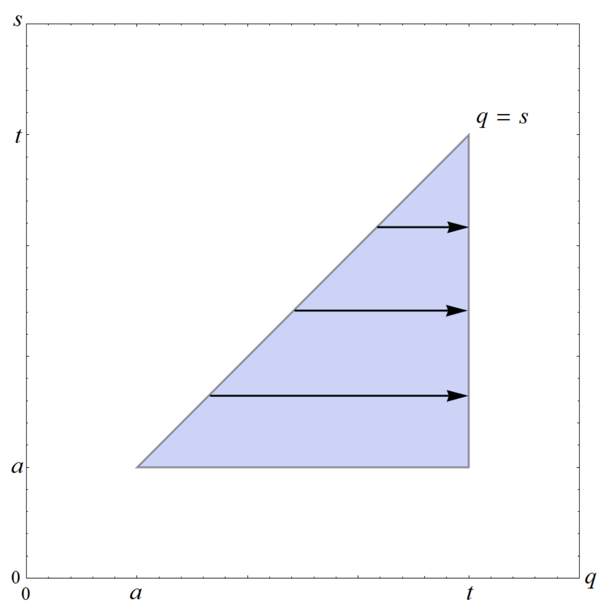
$$\begin{aligned} C_4(t) &= \int^t \csc^2 2q \int^q g(s)\sin 2s\, ds\, dq \\ &= \int^t \int^q (\csc^2 2q) g(s)\sin 2s\, ds\, dq \end{aligned}$$

Suppose that the initial conditions are prescribed at $t = a$: $y(a) = y_0$ and $y'(a) = v_0$. Then the lower limits of integration are both a.

$$C_4(t) = \int_a^t \int_a^q (\csc^2 2q) g(s)\sin 2s\, ds\, dq$$

The domain of integration in the qs-plane is shown below on the left.





Integrate over this domain as shown on the right to switch the order of integration.

$$\begin{aligned} C_4(t) &= \int_a^t \int_s^t (\csc^2 2q) g(s) \sin 2s \, dq \, ds \\ &= \int_a^t g(s) \sin 2s \left(-\frac{1}{2} \cot 2q \right) \bigg|_s^t \, ds \\ &= -\frac{1}{2} \int_a^t g(s) \sin 2s (\cot 2t - \cot 2s) \, ds \end{aligned}$$

The particular solution is then

$$\begin{aligned} y_p(t) &= C_3(t) \cos 2t + C_4(t) \sin 2t \\ &= -\frac{1}{2} \sin 2t \int_a^t g(s) \sin 2s (\cot 2t - \cot 2s) \, ds \\ &= -\frac{1}{2} \int_a^t g(s) (\sin 2s \cos 2t - \sin 2t \cos 2s) \, ds \\ &= \frac{1}{2} \int_a^t g(s) (\sin 2t \cos 2s - \sin 2s \cos 2t) \, ds \\ &= \frac{1}{2} \int_a^t g(s) \sin(2t - 2s) \, ds. \end{aligned}$$

Therefore,

$$\begin{aligned} y(t) &= y_c(t) + y_p(t) \\ &= C_3 \cos 2t + C_4 \sin 2t + \frac{1}{2} \int_a^t g(s) \sin(2t - 2s) \, ds, \end{aligned}$$

where, again, $t = a$ is when the initial conditions are given.