

Solving Differential Equations

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github.com/krishnr/Differential-Equations

SYDE 311

July 31, 2016

1 Power Series Solution of $y'' + p(t)y' + q(t)y = 0$

This is a generalized ODE where $y = y(t)$. The solution is a power series function.

Ordinary Points

A function $f(t)$ is called analytic at t_0 if it has a Taylor Series expansion i.e. all its derivatives from 1 to ∞ exist. For our DE $y'' + p(t)y' + q(t)y = 0$, t_0 is an ordinary point if both $p(t)$ and $q(t)$ are analytic. If this is the case, the solution below solves the DE.

Ordinary Point Solution

1. Use the **trial function**:

$$y(t) = \sum_{n=0}^{\infty} a_n(t - t_0)^n$$

t_0 is an arbitrary center point. If not given, it is assumed to be 0. Our goal is to find a_n .

2. The **index shifted** derivatives of $y(t)$ are:

$$\begin{aligned} y'(t) &= \sum_{n=1}^{\infty} a_n n(t - t_0)^{n-1} = \sum_{n=0}^{\infty} a_{n+1}(n+1)(t - t_0)^n \\ y''(t) &= \sum_{n=2}^{\infty} a_n n(n-1)(t - t_0)^{n-2} = \sum_{n=0}^{\infty} a_{n+2}(n+1)(n+2)(t - t_0)^n \end{aligned}$$

3. Substitute back into the DE.
4. Collect the $(t - t_0)^n$ terms to obtain a **recurrence relation**. It should look like:

$$a_{n+2} = (\dots)a_n$$

5. If possible, generalize the recurrence relation into even and odd cases. Write out a_0 through a_3 and simplify to look for patterns. The generalized even case will be a_{2n} and the odd case will be a_{2n+1} .
6. The final solution is:

$$y(t) = \sum_{n=0}^{\infty} a_{2n}(t-t_0)^{2n} + \sum_{n=0}^{\infty} a_{2n+1}(t-t_0)^{2n+1}$$

Singular Points

If t_0 is not ordinary, it is singular.

Regular Singular Point if $(t-t_0)p(t)$ and $(t-t_0)^2q(t)$ are both analytic. Alternatively, you can check if $\lim_{t \rightarrow t_0} (t-t_0)p(t)$ and $\lim_{t \rightarrow t_0} (t-t_0)^2q(t)$ exist.

Irregular Singular Point otherwise.

Regular Singular Point Solution aka Method of Frobenius

Pretty much the same as the Ordinary Point Solution except you use a slightly different trial function.

1. Use the trial function:

$$y(t) = \sum_{n=0}^{\infty} a_n(t-t_0)^{n+\lambda}$$

The goal is to find λ and a_n .

2. The derivatives of $y(t)$ are:

$$y'(t) = \sum_{n=0}^{\infty} a_n(n+\lambda)(t-t_0)^{n+\lambda-1}$$

$$y''(t) = \sum_{n=0}^{\infty} a_n(n+\lambda)(n+\lambda-1)(t-t_0)^{n+\lambda-2}$$

3. Index shift the derivatives so that the exponents are the same.
4. You will find some of your series start at $n = -1$ while others start at $n = 0$. Unroll the $n = -1$ term so that all the series start at 0 and you can combine them.
5. Extract a quadratic equation for λ . This comes from the unrolling of the $n = -1$ term from the previous step.
6. Solve for λ_1 and λ_2 .
7. For each λ , find the recurrence relation.

8. Write out a_1, a_2, a_3 for each lambda.
9. The linearly independent solution for each λ is:

$$y_{1,2}(t) = (t - t_0)^{\lambda_{1,2}}[a_0 + a_1t + a_2t^2 + \dots]$$

10. The general solution is $y(t) = c_1y_1(t) + c_2y_2(t)$

Note If $\lambda_1 - \lambda_2$ is an integer, you will only get 1 linearly independent solution. The other one is found using the Extended Method of Frobenius.

2 Cauchy-Euler Equation $t^2y'' + aty' + by = 0$

This is a special case of the DE in section 1.

Solution

1. Use the trial function:

$$y(t) = |t|^\lambda$$

2. Find its derivatives:

$$\begin{aligned} y'(t) &= \lambda t^{\lambda-1} \\ y''(t) &= \lambda(\lambda-1)t^{\lambda-2} \end{aligned}$$

3. Substitute into the DE.
4. Collect terms by exponent.
5. Extract quadratic equation for λ (indicial equation) and solve for λ_1 and λ_2 .
6. Only 2 cases we care about:

Distinct real roots $y_1(t) = t^{\lambda_1}$ and $y_2(t) = t^{\lambda_2}$

Repeated real roots $y_1(t) = t^{\lambda_1}$ and $y_2(t) = t^{\lambda_2} \ln(t)$

7. The general solution in both cases is $y(t) = c_1y_1(t) + c_2y_2(t)$

3 Bessel's DE $t^2y'' + ty' + (t^2 - \nu^2)y = 0$

This DE is usually arrived at from other DEs through change of variables, which is most of the work. Actually solving the DE is just a matter of stating the general solution.

Solution

You only get one linearly independent solution:

$$y(t) = c_1 J_0(t) + c_2 Y_0(t)$$

$J_0(t)$ is called the Bessel's function of the 1st kind of order $\nu = 0$. $Y_0(t)$ is called the Bessel's function of the 2nd kind of order 0.

4 Heat Equation $u_t = \kappa u_{xx}$

4.1 Homogenous Boundary Conditions

This means that all the BCs equal 0. There are two types of BCs.

Frozen ends $u(0, t) = u(l, t) = 0$

Insulated ends $u_x(0, t) = u_x(l, t) = 0$

Solution

1. Separation of Variables: assume the solution $u(x, t) = X(x)T(t)$
2. Substitute into the PDE to obtain:

$$\frac{T'(t)}{\kappa T(t)} = \frac{X''(x)}{X(x)} = \sigma$$

3. The solution $T(t)$ is:

$$T(t) = C e^{\kappa \sigma t}$$

4. Assuming $\sigma < 0$, the solution $X(x)$ is:

$$X(x) = A \cos(\sqrt{-\sigma}x) + B \sin(\sqrt{-\sigma}x)$$

5. Plug the BCs into $X(x)$ to find σ :

$$\sigma = -\left(\frac{n\pi}{l}\right)^2$$

6. Substitute $X_n(x)$ and $T_n(t)$ back into $u(x, t)$ to obtain:

$$u(x, t) = \sum_{n=0}^{\infty} u_n(x, t) = \sum_{n=0}^{\infty} B_n \sin\left(\frac{n\pi}{l}x\right) e^{-\left(\frac{n\pi}{l}\right)^2 \kappa t}$$

For frozen ends, you end up with just sin. For insulated ends, you end up with just cos.

7. To find B_n , sub in the IC $u(x, 0) = f(x)$ to find that it resembles the Fourier series, and so:

$$B_n = \frac{1}{l} \int_{-l}^l f(x) \sin\left(\frac{n\pi}{l}x\right) dx$$

8. If the integral is straightforward, solve it, otherwise get it into one of the following forms through trig identities:

$$\frac{1}{l} \int_{-l}^l \cos\left(\frac{n\pi}{l}x\right) \cos\left(\frac{m\pi}{l}x\right) dx = \begin{cases} 1, & n = m \\ 0, & n \neq m \end{cases}$$

$$\frac{1}{l} \int_{-l}^l \cos\left(\frac{n\pi}{l}x\right) \sin\left(\frac{m\pi}{l}x\right) dx = 0$$

$$\frac{1}{l} \int_{-l}^l \sin\left(\frac{n\pi}{l}x\right) \sin\left(\frac{m\pi}{l}x\right) dx = \begin{cases} 1, & n = m \\ 0, & n \neq m \end{cases}$$

9. Plug in B_n back into $u(x, t)$ to complete the solution.

4.2 Non-Homogenous Boundary Conditions

Separation of variables cannot be used because not all the BCs are 0. The plan is to change variables until all the BCs are 0 and then the solution is the same as the homogenous case.

Solution

1. Find the steady-state temperature, i.e. the temperature as $t \rightarrow \infty$:

$$\implies u_t = 0$$

$$\implies u_{xx} = 0 \text{ (from PDE)}$$

$$\implies u''_{ss}(x) = 0$$

$$\implies u'_{ss}(x) = a$$

$$\implies u_{ss}(x) = ax + b$$

2. Sub in the BCs to find u_{ss} .
3. Define $w(x, t)$ to be the transient temperature and:

$$u(x, t) = w(x, t) + u_{ss}(x)$$

4. Rewrite the I/BVP in terms of w . The PDE remains unchanged but the BCs should now be 0.
5. Solve the new I/BVP for $w(x, t)$ using the same method as the previous section on homogenous BCs.
6. Write the final solution in terms of $u(x, t)$.

4.3 Non-Homogenous Heat Problem $u_t = \kappa u_{xx} + g(x, t)$

Solution

1. Assume g can be expressed as a Fourier sine series (if frozen ends) or cosine series (if insulated ends).

$$g(x, t) = \sum_{n=0}^{\infty} g_n(t) \cos\left(\frac{n\pi}{l}x\right)$$
$$g_n(t) = \frac{1}{l} \int_{-l}^l g(x, t) \cos\left(\frac{n\pi}{l}x\right) dx$$

2. The solution is of the form:

$$u(x, t) = \sum_{n=0}^{\infty} T_n(t) \cos\left(\frac{n\pi}{l}x\right)$$

The goal is to find $T_n(t)$.

3. Plug in the $u(x, 0)$ BC to find $T_n(0)$, which serves as initial conditions.
4. Sub everything into the PDE to end up with:

$$T'_n(t) + \kappa\left(\frac{n\pi}{l}\right)^2 T_n(t) = g_n(t)$$

5. Solve the n DEs from the previous equation to solve the problem.

5 Wave Problem $u_{tt} = c^2 u_{xx}$

Here, $0 < x < l, t > 0$.

BCs $u(0, t) = u(l, t) = 0$

ICs $u(x, 0) = f(x)$ and $u_t(x, 0) = g(x)$

Solution

1. Separation of Variables: assume the solution $u(x, t) = X(x)T(t)$
2. Substitute into the PDE to obtain:

$$\frac{T''(t)}{c^2 T(t)} = \frac{X''(x)}{X(x)} = \sigma$$

3. The solution $X(x)$ is:

$$X(x) = c_1 \cos(\sqrt{-\sigma}x) + c_2 \sin(\sqrt{-\sigma}x)$$

4. Plug the BCs into $X(x)$ to find σ :

$$\sigma = -\left(\frac{n\pi}{l}\right)^2$$

5. The solution $T(t)$ is:

$$T_n(t) = a_n \cos\left(\frac{n\pi}{l}ct\right) + b_n \sin\left(\frac{n\pi}{l}ct\right)$$

6. Substitute $X_n(x)$ and $T_n(t)$ back into $u(x, t)$ to obtain:

$$u(x, t) = \sum_{n=0}^{\infty} \left(a_n \cos\left(\frac{n\pi}{l}ct\right) + b_n \sin\left(\frac{n\pi}{l}ct\right) \right) \sin\left(\frac{n\pi}{l}x\right)$$

7. Plug in the ICs to get a_n, b_n .

$$a_n = \frac{1}{l} \int_{-l}^l f(x) \sin\left(\frac{n\pi}{l}x\right) dx$$

$$b_n = \frac{1}{n\pi c} \int_{-l}^l g(x) \sin\left(\frac{n\pi}{l}x\right) dx$$

6 Traveling Wave $u_{tt} = c^2 u_{xx}$

The difference between the Wave Problem and the Traveling Wave is that here, $-\infty < x < \infty$. There are no boundary conditions.

ICs $u(x, 0) = f(x)$ and $u_t(x, 0) = g(x)$

Solution

$$u(x, t) = \frac{1}{2} [f(x - ct) + f(x + ct)] + \frac{1}{2c} \int_{x-ct}^{x+ct} g(s) ds$$

7 Dirichlet Problem $u_{xx} + u_{yy} + u_{zz} = 0$

7.1 All corners 0

Solution

1. Separation of Variables: assume the solution $u(x, y) = X(x)Y(y)$

2. Substitute into the PDE to obtain:

$$-\frac{X''(x)}{X(x)} = \frac{Y''(y)}{Y(y)} = \sigma$$

3. Assuming $\sigma > 0$, the solution $X(x)$ is:

$$X(x) = a \cos(\sqrt{\sigma}x) + b \sin(\sqrt{\sigma}x)$$

4. Plug in the corners into $X(x)$ to find σ :

$$\sigma = \left(\frac{n\pi}{l}\right)^2$$

5. The solution $Y(y)$ is:

$$Y_n(y) = c_1 \cosh\left(\frac{n\pi}{l}y\right) + c_2 \sinh\left(\frac{n\pi}{l}y\right)$$

6. Plug in the corners to find the constants.

7. Substitute $X_n(x)$ and $Y_n(y)$ back into $u(x, y)$ to obtain:

$$u(x, y) = \sum_{n=0}^{\infty} b_n \sin\left(\frac{n\pi}{l}x\right) \sinh\left(\frac{n\pi}{l}y\right)$$

8. Plug in the BCs to get b_n .

7.2 Corners non-zero

Solution

1. Make the corners 0 by using the change of variables:

$$U(x, y) = u(x, y) - \nu(x, y)$$

where

$$\nu(x, y) = \alpha_1 + \alpha_2 x + \alpha_3 y + \alpha_4 xy$$

2. Setting $u = \nu$ at the corners results in a 4x4 system.
3. Once ν is known, write the new problem in terms of $U(x, y)$ and solve using the same method as above.