McGill University
Math 325A: Differential Equations

LECTURE 14 : LINEAR EQUATIONS WITH VARIABLE COEFFICIENTS

HIGHER ORDER DIFFERENTIAL EQUATIONS (VI)

(Text: Chap. 4)

1 Introduction

In this lecture we will give a few techniques for solving certain linear differential equations with non-constant coefficients. We will mainly restrict our attention to second order equations. However, the techniques can be extended to higher order equations. The general second order linear DE is

$$p_0(x)y'' + p_1(x)y' + p_2(x)y = q(x).$$

This equation is called a non-constant coefficient equation if at least one of the functions p_i is not a constant function.

2 Euler Equations

An important example of a non-constant linear DE is Euler's equation

$$x^2y'' + axy' + by = 0,$$

where a, b are constants.

This equation has singularity at $x = 0$. The fundamental theorem of existence and uniqueness of solution holds in the region $x > 0$ and $x, 0$, respectively. So one must solve the problem in the region $x > 0$, or $x < 0$ separately. We first consider the region $x > 0$. This Euler equation can be transformed into a constant coefficient DE by the change of independent variable $x = e^t$. This is most easily seen by noting that

$$\frac{dy}{dt} = \frac{dy}{dx}\frac{dx}{dt} = e^t\frac{dy}{dx} = xy'$$

so that $\frac{dy}{dx} = e^{-t}\frac{dy}{dt}$. In operator form, we have

$$\frac{d}{dt} = e^t\frac{d}{dx} = x\frac{d}{dx}.$$

If we set $D = \frac{d}{dt}$, we have $\frac{d}{dx} = e^{-t}D$ so that

$$\frac{d^2}{dx^2} = e^{-t}De^{-t}D = e^{-2t}e^tDe^{-t}D = e^{-2t}(D-1)D$$

so that $x^2y'' = D(D-1)$. By induction one easily proves that

$$\frac{d^n}{dx^n} = e^{-nt}D(D-1)\cdots(D-n+1)$$

or $x^n y^{(n)} = D(D-1)\cdots(D-n+1)(y)$. With the variable t, Euler's equation becomes

$$\frac{d^2y}{dt^2} + (a-1)\frac{dy}{dt} + by = q(e^t),$$

which is a linear constant coefficient DE. Solving this for y as a function of t and then making the change of variable $t = \ln(x)$, we obtain the solution of Euler's equation for y as a function of x.

For the region $x < 0$, we may let $-x = e^t$, or $|x| = e^t$. Then the equation

$$x^2y'' + axy' + by = 0, \quad (x < 0)$$

is changed to the same form

$$\frac{d^2y}{dt^2} + (a-1)\frac{dy}{dt} + by = 0.$$

Hence, we have the solution $y(t) = y(\ln|x|)$ $(x < 0)$.

The above approach, can extend to solve the n-th order Euler equation

$$x^n y^{(n)} + a_1 x^{n-1} y^{(n-1)} + \cdots + a_n y = q(x),$$

where $a_1, a_2, \dots a_n$ are constants.

Example 1. Solve $x^2y'' + xy' + y = \ln(x)$, $(x > 0)$.

Making the change of variable $x = e^t$ we obtain

$$\frac{d^2y}{dt^2} + y = t$$

whose general solution is $y = A\cos(t) + B\sin(t) + t$. Hence

$$y = A\cos(\ln(x)) + B\sin(\ln(x)) + \ln(x)$$

is the general solution of the given DE.

Example 2. Solve $x^3y''' + 2x^2y'' + xy' - y = 0, \quad (x > 0)$.

This is a third order Euler equation. Making the change of variable $x = e^t$, we get

$$\Big(D(D-1)(D-2) + 2D(D-1) + (D-1)\Big)(y) = (D-1)(D^2+1)(y) = 0$$

which has the general solution $y = c_1e^t + c_2\sin(t) + c_3\cos(t)$. Hence

$$y = c_1x + c_2\sin(\ln(x)) + c_3\cos(\ln(x))$$

is the general solution of the given DE.

3 Exact Equations

The DE $p_0(x)y'' + p_1(x)y' + p_2(x)y = q(x)$ is said to be exact if

$$p_0(x)y'' + p_1(x)y' + p_2(x)y = \frac{d}{dx}(A(x)y' + B(x)y).$$

In this case the given DE is reduced to solving the linear DE

$$A(x)y' + B(x)y = \int q(x)dx + C$$

a linear first order DE. The exactness condition can be expressed in operator form as

$$p_0 D^2 + p_1 D + p_2 = D(AD + B).$$

Since $\frac{d}{dx}(A(x)y' + B(x)y) = A(x)y'' + (A'(x) + B(x))y' + B'(x)y$, the exactness condition holds if and only if $A(x), B(x)$ satisfy

$$A(x) = p_0(x), \quad B(x) = p_1(x) - p_0'(x), \quad B'(x) = p_2(x).$$

Since the last condition holds if and only if $p_1'(x) - p_0''(x) = p_2(x)$, we see that the given DE is exact if and only if

$$p_0'' - p_1' + p_2 = 0$$

in which case

$$p_0(x)y'' + p_1(x)y' + p_2(x)y = \frac{d}{dx}(p_0(x)y' + (p_1(x) - p_0'(x))y).$$

Example 3. Solve the DE $xy'' + xy' + y = x, \quad (x > 0)$.

This is an exact equation since the given DE can be written

$$\frac{d}{dx}(xy' + (x-1)y) = x.$$

Integrating both sides, we get

$$xy' + (x-1)y = x^2/2 + A$$

which is a linear DE. The solution of this DE is left as an exercise.

4 Reduction of Order

If y_1 is a non-zero solution of a homogeneous linear n-th order DE, one can always find a second solution of the form $y = C(x)y_1$ where $C'(x)$ satisfies a homogeneous linear DE of order $n-1$. Since we can choose $C'(x) \neq 0$ we find in this way a second solution $y_2 = C(x)y_1$ which is not a scalar multiple of y_1. In particular for $n = 2$, we obtain a fundamental set of solutions y_1, y_2. Let us prove this for the second order DE

$$p_0(x)y'' + p_1(x)y' + p_2(x)y = 0.$$

If y_1 is a non-zero solution we try for a solution of the form $y = C(x)y_1$. Substituting $y = C(x)y_1$ in the above we get

$$p_0(x)\Big(C''(x)y_1 + 2C'(x)y_1' + C(x)y_1''\Big) + p_1(x)\Big(C'(x)y_1 + C(x)y_1'\Big) + p_2(x)C(x)y_1 = 0.$$

Simplifying, we get

$$p_0 y_1 C''(x) + (p_0 y_1' + p_1 y_1)C'(x) = 0$$

since $p_0 y_1'' + p_1 y_1' + p_2 y_1 = 0$. This is a linear first order homogeneous DE for $C'(x)$. Note that to solve it we must work on an interval where $y_1(x) \neq 0$. However, the solution found can always be extended to the places where $y_1(x) = 0$ in a unique way by the fundamental theorem.

The above procedure can also be used to find a particular solution of the non-homogenous DE $p_0(x)y'' + p_1(x)y' + p_2(x)y = q(x)$ from a non-zero solution of $p_0(x)y'' + p_1(x)y' + p_2(x)y = 0$.

Example 4. Solve $y'' + xy' - y = 0$.

Here $y = x$ is a solution so we try for a solution of the form $y = C(x)x$. Substituting in the given DE, we get

$$C''(x)x + 2C'(x) + x(C'(x)x + C(x)) - C(x)x = 0$$

which simplifies to

$$xC''(x) + (x^2 + 2)C'(x) = 0.$$

Solving this linear DE for $C'(x)$, we get

$$C'(x) = Ae^{-x^2/2}/x^2$$

so that

$$C(x) = A\int \frac{dx}{x^2e^{x^2/2}} + B$$

Hence the general solution of the given DE is

$$y = A_1x + A_2x\int \frac{dx}{x^2e^{x^2/2}}.$$

Example 5. Solve $y'' + xy' - y = x^3e^x$.

By the previous example, the general solution of the associated homogeneous equation is

$$y = A_1x + A_2x\int \frac{dx}{x^2e^{x^2/2}}.$$

Substituting $y_p = xC(x)$ in the given DE we get

$$xC''(x) + (x^2 + 2)C'(x) = x^3e^x.$$

Solving for $C'(x)$ we obtain $C'(x) = x^3e^x$. This gives

$$C(x) = (x^3 - 3x^2 + 6x - 6)e^x + Bx.$$

We can therefore take

$$y_p = (x^4 - 3x^3 + 6x^2 - 6x)e^x$$

so that the general solution of the given DE is

$$y = A_1x + A_2x\int \frac{dx}{x^2e^{x^2/2}} + (x^4 - 3x^3 + 6x^2 - 6x)e^x.$$