

Numerical integration for solving differential equations

After integration, it is natural to consider how to find numerical solutions to differential equations on the computer. Simple equations of motion lead to 2nd order differential equations. In the case of constant acceleration, we see that:

$$v = at + v_0, \quad (1)$$

so,

$$x = \frac{1}{2}at^2 + v_0t + x_0. \quad (2)$$

However, if the force and hence acceleration is related to the position or the velocity in any way, then we cannot just do simple integration in closed form (or at least not simple integration of the form that one typically learns in a first calculus class).¹

There are still plenty of such problems that can be solved in closed form. Let's consider two problems that come up a lot in a first classical mechanics course – the ideal spring which follows Hooke's Law, and the simple pendulum. In an introductory classical mechanics course, we will usually use the small angle approximation, and say that $\sin\theta = \theta$, which then reduces the math for a pendulum's angular motion to being basically the same as the math for a spring's linear motions. It's a pretty good approximation, but it's not quite right, and the differences are something that you could measure in a lab fairly easily.

So, the equations of motion of a pendulum are:

$$\alpha = \frac{-g}{l} \sin\theta = \frac{d\omega}{dt}, \quad (3)$$

and

$$\frac{d\theta}{dt} = \omega. \quad (4)$$

For if we make the small angle approximation that $\sin\theta = \theta$, then we get:

$$\frac{d^2\theta}{dt^2} = \frac{-g}{l} \theta, \quad (5)$$

which we can solve by inspection to give a sine wave with frequency $\sqrt{g/l}$.

If we don't make the small angle approximation, there is no closed form solution to the differential equation.

¹Historically, these problems were solved by perturbation analyses – one would solve a problem that was almost the problem that one wanted to solve, and then figure out how to make small changes to the solution based on the small deviations from the solvable problem. This kind of approach is still often useful for two purposes – (1) it can sometimes guide an efficient approach to finding the numerical solution to the problem and (2) it can sometimes produce simple formula which are approximately correct, and which can guide understanding of what really happens in a way that the outputs of a thousand computer simulations often cannot.

Numerical Integration Of Differential Equations

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