

On a Formula by Cohen, Hubbard and Oesterwinter

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This document proves and generalizes a formula given in [CHO73] to compute the velocity of a body in the context of numerical integration of n -body systems.

Statement

[CHO73] states that

the formula for a velocity component [is] of the form:

$$\dot{x}_{n+1} = \frac{1}{h} \left(x_n - x_{n-1} + h^2 \sum_{i=0}^{12} \beta_i \ddot{x}_{n-i} \right) \quad (1)$$

They then proceed to tabulate explicit values for the (rational) coefficients β_i without explaining how they are computed. This makes it impossible to use this formula for integrators of a different order or to construct similar formulæ for slightly different purposes.

Finite difference formulæ

In this section we prove a backward difference formula that makes it possible to compute an approximation of any derivative of a function on an equally-spaced grid at any desired order. We then derive a corollary based on the second derivative $f''(x)$ that is useful for the following sections.

Lemma. *Given a sufficient regular function $f(x)$ and two integers $m \leq n$, there exists a family of rational numbers $\lambda_{n,v}^m$, with $0 \leq v \leq n$, such that:*

$$f^{(m)}(x_0) = \frac{(-1)^m}{h^m} \sum_{v=0}^n \lambda_{n,v}^m f(x_0 - vh) + \mathcal{O}(h^{n-m+1}) \quad (2)$$

Furthermore, the $\lambda_{n,v}^m$ are independent from x_0 and h .

Proof. [For88] gives finite difference formulæ for any order and for kernels of arbitrary size. Given a family $\alpha = (\alpha_0, \alpha_1, \dots, \alpha_N)$ of points (which may not be equidistant), the m -th derivative at any point x_0 may be approximated to order $n - m + 1$ as:

$$f^{(m)}(x_0) \cong \sum_{v=0}^n \delta_{n,v}^m(\alpha) f(\alpha_v)$$

where $m \leq n$ and the coefficients $\delta_{n,v}^m$ are dependent on α but independent of f .

If the α are equally spaced with step $-h$ (i.e., $\alpha_v = x_0 - vh$) then we can write a backward formula as follows:

$$f^{(m)}(x_0) = \sum_{v=0}^n \delta_{n,v}^m(\alpha) f(x_0 - vh) + \mathcal{O}(h^{n-m+1}) \quad (3)$$

In this case equation (3.8) from [For88] may be rewritten as follows, restoring x_0 :

$$\begin{aligned}\delta_{n,v}^m &= \frac{1}{\alpha_n - \alpha_v} ((\alpha_n - x_0)\delta_{n-1,v}^m - m\delta_{n-1,v}^{m-1}) \\ &= \frac{1}{(v-n)h} (-nh\delta_{n-1,v}^m - m\delta_{n-1,v}^{m-1})\end{aligned}\quad (4)$$

It is possible to extract the powers of h from the coefficients by defining, for $v < n$:

$$\lambda_{n,v}^m := \delta_{n,v}^m(\alpha)(-1)^m h^m$$

Substituting into equation (4) we obtain:

$$\lambda_{n,v}^m = \frac{1}{n-v} (n\lambda_{n-1,v}^m - m\lambda_{n-1,v}^{m-1})$$

and we see that $\lambda_{n,v}^m$ is independent from x_0 and h and therefore that $\delta_{n,v}^m$ is independent from x_0 .

Note that the definition of $\lambda_{n,v}^m$ extends immediately to $n = v$, that is to $\lambda_{n,n}^m$, using equation (3.10) of [For88].

Now knowing that:

$$\delta_{n,v}^m(\alpha) = (-1)^m \frac{\lambda_{n,v}^m}{h^m}$$

it is straightforward to rewrite equation (3) to obtain equation (2), thus demonstrating the lemma. \square

Corollary. *Applying the lemma to the second derivative $f''(x)$ gives the following result when $m \geq 2$:*

$$f^{(m)}(x_0) = \frac{(-1)^m}{h^{m-2}} \sum_{v=0}^{n-2} \lambda_{n-2,v}^{m-2} f''(x_0 - vh) + \mathcal{O}(h^{n-m+1}) \quad (5)$$

\square

A formula for symmetric linear multistep integrators

In this section we derive a formula suitable for computing the velocity of a body knowing its positions and accelerations at preceding times. This is the formula we use after integration using a symmetry linear multistep integrator.

Proposition. *Given a sufficient regular function $f(x)$ there exists a family of rational numbers $\eta_{n,v}$, with $0 \leq v \leq n-2$, such that:*

$$f'(x_0) = \frac{1}{h} \left(f(x_0) - f(x_0 - h) + h^2 \sum_{v=0}^{n-2} \eta_{n,v} f''(x_0 - vh) \right) + \mathcal{O}(h^n) \quad (6)$$

Proof. We start by writing the Taylor series of $f(x_0 - h)$ for h close to 0, extracting the leading terms:

$$\begin{aligned}f(x_0 - h) &= \sum_{m=0}^{\infty} \frac{f^{(m)}(x_0)}{m!} (-1)^m h^m \\ &= f(x_0) - hf'(x_0) + \sum_{m=2}^{\infty} \frac{f^{(m)}(x_0)}{m!} (-1)^m h^m \\ &= f(x_0) - hf'(x_0) + \sum_{m=2}^n \frac{f^{(m)}(x_0)}{m!} (-1)^m h^m + \mathcal{O}(h^{n+1})\end{aligned}\quad (7)$$

Injecting the expression from corollary (5) into this series we find:

$$f(x_0 - h) = f(x_0) - hf'(x_0) + h^2 \sum_{m=2}^n \sum_{v=0}^{n-2} \frac{\lambda_{n-2,v}^{m-2}}{m!} f''(x_0 - vh) + \mathcal{O}(h^{n+1})$$

The summations are independent and can be exchanged:

$$f(x_0 - h) = f(x_0) - hf'(x_0) + h^2 \sum_{v=0}^{n-2} \left(\sum_{m=2}^n \frac{\lambda_{n-2,v}^{m-2}}{m!} \right) f''(x_0 - vh) + \mathcal{O}(h^{n+1})$$

If we define:

$$\eta_{n,v} := \sum_{m=2}^n \frac{\lambda_{n-2,v}^{m-2}}{m!}$$

the equation (6) follows immediately. \square

The Cohen-Hubbard-Osterwinder formula

In this section we derive the Cohen-Hubbard-Osterwinder formula, equation (1).

Proposition. *Given a sufficient regular function $f(x)$ there exists a family of rational numbers $\beta_{n,v}$, with $0 \leq v \leq n-2$, such that:*

$$f'(x_0 + h) = \frac{1}{h}(f(x_0) - f(x_0 - h)) + h \sum_{v=0}^{n-2} \beta_{n,v} f''(x_0 - vh) + \mathcal{O}(h^n)$$

Proof. We start by writing the Taylor series of $f'(x_0 + h)$ for h close to 0:

$$\begin{aligned} f'(x_0 + h) &= f'(x_0) + \sum_{m=2}^{\infty} \frac{h^{m-1}}{(m-1)!} f^{(m)}(x_0) \\ &= f'(x_0) + \sum_{m=2}^n \frac{h^{m-1}}{(m-1)!} f^{(m)}(x_0) + \mathcal{O}(h^n) \end{aligned}$$

and we replace $f'(x_0)$ with its value from equation (7):

$$f'(x_0 + h) = \frac{1}{h}(f(x_0) - f(x_0 - h)) + \sum_{m=2}^n \frac{h^{m-1}}{(m-1)!} \left(1 + \frac{(-1)^m}{m} \right) f^{(m)}(x_0) + \mathcal{O}(h^n)$$

As we did above, we replace $f^{(m)}(x_0)$ using its expression from corollary (5) to obtain:

$$f'(x_0 + h) = \frac{1}{h}(f(x_0) - f(x_0 - h)) + h \sum_{m=2}^n \left(\frac{1}{(m-1)!} \left((-1)^m + \frac{1}{m} \right) \sum_{v=0}^{n-2} \lambda_{n-2,v}^{m-2} f''(x_0 - vh) \right) + \mathcal{O}(h^n)$$

If we exchange the summations and define:

$$\beta_{n,v} = \sum_{m=2}^n \frac{\lambda_{n-2,v}^{m-2}}{(m-1)!} \left((-1)^m + \frac{1}{m} \right)$$

we obtain the desired result, which is a reformulation of equation (1) where β_i in [CHO73] is our $\beta_{14,i}$. \square

References

- [CHO73] C. J. Cohen, E. C. Hubbard and C. Oesterwinter. *Astronomical Papers Prepared for the Use of the American Ephemeris and Nautical Almanac – Elements of the Outer Planets for One Million Years*. Vol. XXII. I. United States Government Printing Office, 1973.
- [For88] B. Fornberg. “Generation of Finite Difference Formulas on Arbitrarily Spaced Grids”. In: *Mathematics of Computation* 51 (Oct. 1988), pp. 699–706.
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