

## Research Article

# Dynamics of Numerics of Nonautonomous Equations with Periodic Solutions: Introducing the Numerical Floquet Theory

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Nonautonomous systems with periodic solutions are encountered frequently in applications. In this paper, we will consider simple systems whose solutions are periodic with a known period. Their transformations under linearized collocation methods is investigated, using a technique called stroboscopic sampling, a discrete version of the well-known Poincaré map. It is shown that there is an inextricable relationship between AN stability (or BN stability) of the numerical methods and the correct qualitative behaviour of solutions.

## 1. Introduction

Let

$$x' = f(x, t), \quad x(0) = x_0, \quad (1)$$

where  $f: I \subset \mathbb{R} \times \mathbb{R} \rightarrow \mathbb{R}$ , be a scalar ordinary differential equation in which  $f(x, t)$  is a periodic function of  $t$  with prime period  $T$ .

The detailed dynamics of numerics for nonautonomous ODEs has notably been lacking. Although any nonautonomous ODE can be transformed to an autonomous one, thereby increasing the dimension by one, the familiar dynamics of autonomous equations which is centered around the notion of equilibrium points [1] is lost. In certain special cases, this notion is replaced by that of periodicity. It is on these special cases that we will focus our attention. Stuart [2] proved using the bifurcation theory that for reaction-diffusion-convection equations, linearised instability implies the existence of spurious periodic solutions. Our approach differs from that of Stuart, who considered partial differential equations. Nonautonomous ODEs where  $f$  is periodic in  $t$  are very common in applications such as population dynamics with seasonal parameters or periodically forced systems.

Under certain conditions on  $f$ , (1) has a unique  $T$ -periodic solution [3]. We will assume that the solution is approximated by a linearized one-point collocation method as in Foster and Khumalo [4]. Our objective is to determine,

for each  $f$  under consideration, whether the numerical scheme has the same dynamical behaviour as the differential equation. In particular, we will consider cases in which the ODE has a unique, asymptotically stable periodic solution and establish conditions under which the numerical methods have the same dynamics. These special cases will take the following form:

- (i)  $f$  linear:  $f(x, t) = a(t)x + b(t)$ , where  $a(t)$  and  $b(t)$  are  $C^1$   $T$ -periodic functions of  $t$ .
- (ii)  $f$  nonlinear:  $f = a(t)g(x) + b(t)$ , where  $g(x)$  is a  $C^2$  nonlinear function of  $x$ .

The linearized one-point collocation methods for the scalar nonautonomous equation (1) are given by

$$\begin{aligned} x_{n+1} &= \left( x_n + hf(t_n, x_n) + c_1 h^2 \left( \frac{\partial f}{\partial t} \right) (t_n, x_n) \right. \\ &\quad \left. - c_1 h x_n \left( \frac{\partial f}{\partial x} \right) (t_n, x_n) \right) \\ &= \left( 1 - c_1 h \left( \frac{\partial f}{\partial x} \right) (t_n, x_n) \right)^{-1}. \end{aligned} \quad (2)$$

where  $0 \leq c_1 \leq 1$ .

For a discussion of collocation methods in general, see Hairer et al. [5].

We begin with a description of the dynamical systems theory approach, which will be used in determining the conditions under which the methods have the same dynamical

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