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Frequency dependent iteration method for forced nonlinear oscillators

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Abstract

A new iteration method for nonlinear vibrations has been developed by decomposing the periodic solution in two parts corresponding to low and high harmonics. For a nonlinear forced oscillator, the iteration schema is proposed with different formulations for these two parts. Then, the schema is deduced by using the harmonic balance technique. This method has proven to converge to the periodic solutions provided that a convergence condition is satisfied. The convergence is also demonstrated analytically for linear oscillators. Moreover, the new method has been applied to Duffing oscillators as an example. The numerical results show that each iteration schema converges in a domain of the excitation frequency and it can converge to different solutions of the nonlinear oscillator.

Keywords: Forced nonlinear oscillator, harmonic balance method, iteration procedure, Duffing oscillator.

1. Introduction

The harmonic balance method (HBM) has many applications in nonlinear dynamics. The original principle of this method is to express the periodic solution in terms of Fourier series with limited numbers of harmonics and to substitute this expression to the dynamic equation in order to find out balance

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9 of all harmonics. A typical difficulty of this method is linked to the dependence
10 of the quality of the approach on the way to carry enough terms in the solution
11 and check the order of the coefficients for all the neglected harmonics [1, 2].
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14 Some alternative techniques based on HBM have been developed in order
15 to solve this difficulty. The Galerkin procedure [3–6] was used to calculate
16 incrementally the Fourier coefficients of the classical HBM. Another technique
17 called the iteration procedures were presented by Mickens [7, 8] and applied to
18 different kinds of non-linearities [9, 10]. The high dimensional harmonic balance
19 (HDHB) was developed by Hall et al. [11]. This method is based on a constant
20 Fourier transformation matrix which is an approximation of the matrix related
21 to the non-linearity deduced from the classical HBM. This method has some
22 advantages in calculation in case of high dimension, but it can lead to non-
23 physical solutions [12–14]. Recently, other new methods based on HBM were
24 developed by Cochelin et al. [15–17] and Ju et al. [18–20].
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31 In this paper, we propose a new method for forced nonlinear oscillators based
32 on the iteration procedures and HBM. The existing methods propose to use the
33 same iteration schema for all harmonics. This new method provides different
34 schemas which adapt to the frequency of the force. By decomposing the pe-
35 riodical solution in low and high harmonic components, an iteration schema
36 is presented and then developed by using HBM. The schemas are proved to
37 converge to the periodic solution, provided that a sufficient condition is satis-
38 fied. Thus, the harmonic decomposition is a new way to build iteration schemas
39 which could be applied to other problems using HMB (e.g. the high dimensional
40 problems). Moreover, this method is demonstrated to converge to the analytic
41 solution of a linear oscillator and it is applied to a forced Duffing oscillator. The
42 numerical results show that each iteration schema converges in each range of the
43 excitation frequency and it can converge to different solutions of the oscillator.
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9 **2. Iteration schemas**

10 Let's consider a forced nonlinear oscillator given by

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$$\frac{d^2 u}{dt^2} + \beta \dot{u} + \omega_0^2 u + f(u, \dot{u}) = A \cos \Omega t \quad (1)$$

14 where $f(u, \dot{u})$ is a nonlinear function. This equation is rewritten to read

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$$\frac{d^2 u}{dt^2} + \Omega^2 u = (\Omega^2 - \omega_0^2)u - \beta \dot{u} - f(u, \dot{u}) + A \cos \Omega t \equiv G(u, \dot{u}) \quad (2)$$

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20 A classical iteration schema is often proposed as follows

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$$\frac{d^2 u_{k+1}}{dt^2} + \Omega^2 u_{k+1} = \mathcal{L}(G(u_i, \dot{u}_j)_{i,j \leq k}) \quad (3)$$

24 where \mathcal{L} is a linear form which is chosen for each function $G(u, \dot{u})$ in order to meet
25 the convergence. Now we will build a different iteration schema by considering
26 the periodic solution defined by series $\{q_{nk}\}, \{p_{nk}\}$ (with $1 \leq n \leq N$) as follows

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$$u_{Nk}(t) = \frac{q_{0k}}{2} + \sum_{n=1}^N q_{nk} \cos n\Omega t + p_{nk} \sin n\Omega t \quad (4)$$

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32 For each \mathcal{N} ($0 \leq \mathcal{N} \leq N$), we decompose u_{Nk} into two terms which corre-
33 spond to low and high harmonics as follows

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$$X_k(t) = \frac{q_{0k}}{2} + \sum_{n=1}^{\mathcal{N}} q_{nk} \cos n\Omega t + p_{nk} \sin n\Omega t \quad (5)$$

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$$Y_k(t) = \sum_{n=\mathcal{N}+1}^N q_{nk} \cos n\Omega t + p_{nk} \sin n\Omega t \quad (6)$$

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$$u_{Nk}(t) = X_k(t) + Y_k(t) \quad (7)$$

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45 Then, the proposed iteration schema is

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$$\frac{d^2 Y_{k+1}}{dt^2} + \beta \dot{X}_{k+1} + \omega_0^2 X_{k+1} = A \cos \Omega t - f(u_{Nk}, \dot{u}_{Nk}) \quad (8)$$

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$$- \frac{d^2 X_k}{dt^2} - \beta \dot{Y}_k - \omega_0^2 Y_k$$

52 Here, we take the initial values (i.e. $k = 1$) by $q_{n1} = p_{n1} = 0$. Now we will
53 develop this schema by using the harmonic balance technique. By performing

the Fourier series development of equation (8), we obtain the following results

$$\begin{aligned} \frac{1}{T} \int_0^T \left(\frac{d^2 Y_{k+1}}{dt^2} + \beta \dot{X}_{k+1} + \omega_0^2 X_{k+1} \right) \cos n\Omega t \, dt &= A\delta_{1n} - \mathcal{C}_{nk} \\ &- \frac{1}{T} \int_0^T \left(\frac{d^2 X_k}{dt^2} + \beta \dot{Y}_k + \omega_0^2 Y_k \right) \cos n\Omega t \, dt \end{aligned} \quad (9)$$

$$\begin{aligned} \frac{1}{T} \int_0^T \left(\frac{d^2 Y_{k+1}}{dt^2} + \beta \dot{X}_{k+1} + \omega_0^2 X_{k+1} \right) \sin n\Omega t \, dt &= -\mathcal{S}_{nk} \\ &- \frac{1}{T} \int_0^T \left(\frac{d^2 X_k}{dt^2} + \beta \dot{Y}_k + \omega_0^2 Y_k \right) \sin n\Omega t \, dt \end{aligned} \quad (10)$$

where $T = \frac{2\pi}{\Omega}$; $\delta_{1n} = 1$ if $n = 1$ and $\delta_{1n} = 0$ if other. $\mathcal{C}_{nk}, \mathcal{S}_{nk}$ are the Fourier coefficients of $f(u_{Nk}, \dot{u}_{Nk})$

$$\begin{cases} \mathcal{C}_{nk} = \frac{2}{T} \int_0^T f(u_{Nk}, \dot{u}_{Nk}) \cos n\Omega t \, dt \\ \mathcal{S}_{nk} = \frac{2}{T} \int_0^T f(u_{Nk}, \dot{u}_{Nk}) \sin n\Omega t \, dt \end{cases} \quad (11)$$

Thereafter, by substituting equations (5) and (6) into equations (9) and (10),

we obtain

For $n = 0$

$$\omega_0^2 q_{0(k+1)} = -\mathcal{C}_{0k}$$

For $0 < n \leq \mathcal{N}$

$$\begin{aligned} \beta n \Omega p_{n(k+1)} + \omega_0^2 q_{n(k+1)} &= A\delta_{n1} - \mathcal{C}_{nk} + n^2 \Omega^2 q_{nk} \\ -\beta n \Omega q_{n(k+1)} + \omega_0^2 p_{n(k+1)} &= -\mathcal{S}_{nk} + n^2 \Omega^2 p_{nk} \end{aligned}$$

For $\mathcal{N} < n \leq N$

$$\begin{aligned} -n^2 \Omega^2 q_{n(k+1)} &= A\delta_{n1} - \mathcal{C}_{nk} - \omega_0^2 q_{nk} - \beta n \Omega p_{nk} \\ -n^2 \Omega^2 p_{n(k+1)} &= -\mathcal{S}_{nk} - \omega_0^2 p_{nk} + \beta n \Omega q_{nk} \end{aligned}$$

Finally, we have deduced the iteration schema (8) to the results in Table 1 where $\{p_{nk}\}, \{q_{nk}\}$ are represented as recurrent sequences. By taking the initial values ($p_{n1} = q_{n1} = 0$), we can compute these series for a number of iteration K to get the solution of equation (1). Here, we have one iteration schema

corresponding to each value of \mathcal{N} . In the next section, we will prove that these schemas converge to the periodic solution of equation (1) if a sufficient condition is satisfied.

Table 1: Frequency dependent iteration schema

$n = 0$	$q_{n(k+1)} = -\frac{\mathcal{C}_{0k}}{\omega_0^2} \quad ; \quad p_{n(k+1)} = 0$
$0 < n \leq \mathcal{N}$	$p_{n(k+1)} = \frac{n^2\Omega^2(\beta n\Omega q_{nk} + \omega_0^2 p_{nk})}{(\beta n\Omega)^2 + \omega_0^4} - \frac{\beta n\Omega \mathcal{C}_{nk} + \omega_0^2 \mathcal{S}_{nk} + \beta n\Omega A\delta_{n1}}{(\beta n\Omega)^2 + \omega_0^4}$ $q_{n(k+1)} = \frac{n^2\Omega^2(-\beta n\Omega p_{nk} + \omega_0^2 q_{nk})}{(\beta n\Omega)^2 + \omega_0^4} + \frac{\beta n\Omega \mathcal{S}_{nk} - \omega_0^2 \mathcal{C}_{nk} + \omega_0^2 A\delta_{n1}}{(\beta n\Omega)^2 + \omega_0^4}$
$\mathcal{N} < n \leq N$	$q_{n(k+1)} = \frac{\omega_0^2}{n^2\Omega^2} q_{nk} + \frac{\beta}{n\Omega} p_{nk} + \frac{\mathcal{C}_{nk}}{n^2\Omega^2} - \frac{A\delta_{n1}}{n^2\Omega^2}$ $p_{n(k+1)} = \frac{\omega_0^2}{n^2\Omega^2} p_{nk} - \frac{\beta}{n\Omega} q_{nk} + \frac{\mathcal{S}_{nk}}{n^2\Omega^2}$

3. Sufficient condition of convergence

Lemma: If $f \in \mathcal{C}^1$ and if the series of functions $\{u_{Nk}\}$ defined by equation (4) and the schema in Table 1 is uniformly convergent when N, k tends to infinity, their limit is a periodic solution of equation (1).

Demonstration: Suppose that $u_{Nk}(t)$ converges uniformly to $u(t)$. We have to prove that

- (i) $u(t)$ is periodic of period T
- (ii) $u(t)$ is a solution of equation (1).

We prove (i) by contrary. Suppose that it exists τ such that $|u(\tau) - u(\tau + T)| = a > 0$. Because $u_{Nk}(t)$ is uniformly convergent, for $0 < 2\epsilon < a$ it exists M, K such that $\forall N > M, k > K$ we have

$$|u_{Nk}(\tau) - u(\tau)| < \epsilon$$

$$|u_{Nk}(\tau + T) - u(\tau + T)| < \epsilon$$

In addition, we have $u_{Nk}(\tau) = u_{Nk}(\tau + T)$. Thus

$$a = |u(\tau) - u(\tau + T)| \leq |u_{Nk}(\tau) - u(\tau)| + |u_{Nk}(\tau) - u(\tau + T)| < 2\epsilon$$

The last inequality cannot be true because $2\epsilon < a$. By consequence, $u(t)$ is
60 periodic.

To prove (ii), it is sufficient to show that $\forall \epsilon > 0, \exists M', K'$ such that

$$|\ddot{u}_{Nk} + \omega_0^2 u_{Nk} + f(u_{Nk}, \dot{u}_{Nk}) - K \cos \Omega t| < C\epsilon \quad \forall N > M', k > K' \quad (12)$$

where C is a constant.

By using the triangular inequality, we have

$$\begin{aligned} & \left| \ddot{u}_{N(k+1)} + \omega_0^2 u_{N(k+1)} + f(u_{N(k+1)}, \dot{u}_{N(k+1)}) - \Gamma \cos \Omega t \right| \leq \omega_0^2 |Y_{k+1} - Y_k| \\ & + \beta \left| \dot{Y}_{k+1} - \dot{Y}_k \right| + \left| \frac{d^2}{dt^2} (X_{k+1} - X_k) \right| + \left| f(u_{N(k+1)}, \dot{u}_{N(k+1)}) - f(u_{Nk}, \dot{u}_{Nk}) \right| \\ & + \left| \frac{d^2}{dt^2} (Y_{k+1} + X_k) + \beta (\dot{X}_{(k+1)} + \dot{Y}_k) + \omega_0^2 (X_{k+1} + Y_k) + f(u_{Nk}, \dot{u}_{Nk}) - A \cos \Omega t \right| \end{aligned}$$

We note f_a, f_b, f_c, f_d and f_e the five terms of the last inequality, that means

$$\begin{aligned} f_a &= \omega_0^2 |Y_{k+1} - Y_k| \\ f_b &= \beta \left| \dot{Y}_{k+1} - \dot{Y}_k \right| \\ f_c &= \left| \frac{d^2}{dt^2} (X_{k+1} - X_k) \right| \\ f_d &= \left| f(u_{N(k+1)}, \dot{u}_{N(k+1)}) - f(u_{Nk}, \dot{u}_{Nk}) \right| \\ f_e &= \left| \frac{d^2}{dt^2} (Y_{k+1} + X_k) + \beta (\dot{X}_{(k+1)} + \dot{Y}_k) \right. \\ & \quad \left. + \omega_0^2 (X_{k+1} + Y_k) + f(u_{Nk}, \dot{u}_{Nk}) - A \cos \Omega t \right| \end{aligned}$$

In order to prove (12), we have to prove that f_a, f_b, \dots, f_e are measured by ϵ .

Because u_{Nk} is uniformly convergent, it is clear that f_a is measured by ϵ .

To prove that f_b and f_c are measured by ϵ , it is sufficient, for example, to take
65 the definition of X_{mk} from equation (5) with remark that

$$\begin{aligned} f_c &= \left| \frac{d^2}{dt^2} (X_{(k+1)} - X_k) \right| \\ &= \left| \sum_{n=1}^m n^2 \Omega^2 [(p_{n(k+1)} - p_{nk}) \sin n\Omega t + (q_{n(k+1)} - q_{nk}) \cos n\Omega t] \right| \\ &\leq \sum_{n=1}^m n^2 \Omega^2 (|p_{n(k+1)} - p_{nk}| + |q_{n(k+1)} - q_{nk}|) \end{aligned}$$

As the series $\{u_{Nk}\}$ converge uniformly, the series p_{nk}, q_{nk} are uniformly convergent when k tends to infinity. Thus, f_b and f_c are measured by ϵ .

In order to measure f_d , we use a following property: for $f \in \mathcal{C}^1$, it exists C such that $|f(u) - f(\tilde{u})| \leq C\epsilon$ when $|u - \tilde{u}| < \epsilon$. As the series u_{Nk} converges uniformly, we can chose k large enough for $|u_{N(k+1)} - u_{Nk}| < \epsilon$. By consequence, f_d is measured by ϵ .

For f_e , by using the iteration schema in Table 1, we obtain

$$\begin{aligned} & \left| \frac{d^2}{dt^2} (Y_{(k+1)} + X_k) + \Omega^2 (X_{(k+1)} - X_k) + \omega_0^2 u_{Nk} + f(u_{Nk}, \dot{u}_{Nk}) - A \cos \Omega t \right| \\ &= \left| f(u_{mk}, \dot{u}_{mk}) - \left(\frac{\mathcal{C}_{0k}}{2} + \sum_{n=1}^m \mathcal{C}_{nk} \cos n\Omega t + \mathcal{S}_{nk} \sin n\Omega t \right) \right| \end{aligned}$$

Thus, f_e is exactly the difference between the function $f(u_{Nk}, \dot{u}_{Nk})$ and its Fourier series development. Because u_{Nk} is periodic and bounded, $f(u_{Nk}, \dot{u}_{Nk})$ is also periodic and bounded. Thus, this difference is measured by ϵ when N is large enough. Therefore, the five terms are measured by ϵ , and the lemma is proved.

4. Examples

4.1. Linear oscillator

We consider a forced linear oscillator, i.e. $f(u, \dot{u}) = 0$. The iteration schema in Table 1 becomes

$$\begin{aligned} n = 0 & \quad q_{0(k+1)} = 0 \\ 1 \leq n \leq \mathcal{N} & \quad p_{n(k+1)} = \frac{n^2 \Omega^2 (\beta n \Omega q_{nk} + \omega_0^2 p_{nk})}{(\beta n \Omega)^2 + \omega_0^4} + \frac{\beta n \Omega A \delta_{n1}}{(\beta n \Omega)^2 + \omega_0^4} \\ & \quad q_{n(k+1)} = \frac{n^2 \Omega^2 (-\beta n \Omega p_{nk} + \omega_0^2 q_{nk})}{(\beta n \Omega)^2 + \omega_0^4} + \frac{\omega_0^2 A \delta_{n1}}{(\beta n \Omega)^2 + \omega_0^4} \\ \mathcal{N} \leq n \leq N & \quad q_{n(k+1)} = \frac{\omega_0^2}{n^2 \Omega^2} q_{nk} + \frac{\beta}{n \Omega} p_{nk} - \frac{A \delta_{n1}}{n^2 \Omega^2} \\ & \quad p_{n(k+1)} = \frac{\omega_0^2}{n^2 \Omega^2} p_{nk} - \frac{\beta}{n \Omega} q_{nk} \end{aligned}$$

We will prove that when the schema converges, its limit is the analytic solution.

80 *Case $\mathcal{N} = 0$*

For $n \geq 2$, we have

$$\begin{aligned} q_{n(k+1)} + ip_{n(k+1)} &= \left(\frac{\omega_0^2}{n^2\Omega^2} - \frac{i\beta}{n\Omega} \right) (q_{nk} + ip_{nk}) \\ q_{n(k+1)} - ip_{n(k+1)} &= \left(\frac{\omega_0^2}{n^2\Omega^2} + \frac{i\beta}{n\Omega} \right) (q_{nk} - ip_{nk}) \end{aligned}$$

The last equations define two geometrical sequences and they converge if and only if $\left| \frac{\omega_0^2}{n^2\Omega^2} + \frac{i\beta}{n\Omega} \right| < 1$; their limits are zeros (i.e., $q_{nk}, p_{nk} \rightarrow 0$ when $k \rightarrow \infty$).

For $n = 1$, we have

$$\begin{aligned} q_{1(k+1)} + ip_{1(k+1)} - A_1 &= \left(\frac{\omega_0^2}{\Omega^2} - \frac{i\beta}{\Omega} \right) (q_{1k} + ip_{1k} - A_1) \\ q_{1(k+1)} - ip_{1(k+1)} - A_2 &= \left(\frac{\omega_0^2}{\Omega^2} + \frac{i\beta}{\Omega} \right) (q_{1k} - ip_{1k} - A_2) \end{aligned} \quad (13)$$

where $A_1 = -A/(\Omega^2 - \omega_0^2 + i\beta\Omega)$ and $A_2 = -A/(\Omega^2 - \omega_0^2 - i\beta\Omega)$. The last equations define also two geometrical sequences which converge to zeros with the same condition for $n \geq 2$. By consequence, the limits of $\{q_{1k}\}$ and $\{p_{1k}\}$ are

$$\begin{cases} \mathbf{q}_1 = \frac{(\omega_0^2 - \Omega^2)A}{(\omega_0^2 - \Omega^2)^2 + (\beta\Omega)^2} \\ \mathbf{p}_1 = \frac{\beta\Omega A}{(\omega_0^2 - \Omega^2)^2 + (\beta\Omega)^2} \end{cases} \quad (14)$$

Equation (14) is exactly the analytic solution of the forced linear oscillator. Thus, the sufficient condition is thus justified in this case. **In addition, equation (13) shows that the schema converges linearly and the convergence rate is calculated by**

$$\mu = \left| \frac{\omega_0^2}{\Omega^2} + \frac{i\beta}{\Omega} \right| \quad (15)$$

The condition of the convergence $\mu < 1$ can be rewritten as $\Omega^4 - \omega_0^4 > (\beta\Omega)^2$. It means that Ω is larger than the resonance frequency of the oscillator Ω_r .

85 *Case $\mathcal{N} = 1$*

For $n \geq 2$, we have the same results with the previous case, i.e., $q_{nk}, p_{nk} \rightarrow 0$ when $k \rightarrow \infty$ if and only if $\left| \frac{\omega_0^2}{n^2\Omega^2} + \frac{i\beta}{n\Omega} \right| < 1$ for $n \geq 2$.

For $n = 1$, we have

$$q_{1(k+1)} + ip_{1(k+1)} - A_1 = \frac{\Omega^2}{-i\beta\Omega + \omega_0^2}(q_{1k} + ip_{1k} - A_1)$$

$$q_{1(k+1)} - ip_{1(k+1)} - A_2 = \frac{\Omega^2}{i\beta\Omega + \omega_0^2}(q_{1k} - ip_{1k} - A_2)$$

We see that the last two equations define also two geometrical sequences which converge if and only if $\left| \frac{\Omega^2}{i\beta\Omega + \omega_0^2} \right| < 1$. The condition of convergence for $n = 1$ and $n \geq 2$ of the schema can be rewritten as follows

$$\begin{cases} \Omega^4 - \omega_0^4 < (\beta\Omega)^2 \\ 16\Omega^4 - \omega_0^4 > 4(\beta\Omega)^2 \end{cases} \quad (16)$$

We deduce that the iteration schema $\mathcal{N} = 1$ converges linearly when Ω is smaller than the resonance frequency **and the convergence rate is**

$$\mu = \left| \frac{\Omega^2}{i\beta\Omega + \omega_0^2} \right| \quad (17)$$

Case $\mathcal{N} \geq 2$

Similarly, the schema converges linearly to the analytic solution if and only if

$$\begin{cases} \mathcal{N}^4\Omega^4 - \omega_0^4 < (\beta\mathcal{N}\Omega)^2 \\ (\mathcal{N} + 1)^4\Omega^4 - \omega_0^4 > (\beta(\mathcal{N} + 1)\Omega)^2 \end{cases} \quad (18)$$

Remark: From equations (13) and (17), when $\Omega \simeq \Omega_r$, the convergence rate μ can be approached by

$$\mu \simeq \left(1 - \frac{\Delta\Omega}{\Omega_r} \right)^2 \quad (19)$$

where $\Delta\Omega = |\Omega - \Omega_r|$. It means that $\mu^K \simeq 1 - 2K \frac{\Delta\Omega}{\Omega_r}$. Thus, the number of iteration can be estimated by $K \sim \frac{1}{2} \frac{\Omega_r}{\Delta\Omega}$.

Numerical example

The iteration method is used for a forced linear oscillator with $\omega_0 = 1$, $A = 1$. Figure 1 shows the amplitude $\mathcal{A} = \sqrt{q_1^2 + p_1^2}$ in function of the excitation frequency Ω with different values of the damping coefficient β . Here, we take

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95 the number of harmonics $N = 3$ and the number of iteration $K = 300$ for all frequencies Ω . The figure shows that the iteration method converges to the analytic solution. Particularly, the schema with $\mathcal{N} = 0$ is convergent for low frequency Ω and the schema with $\mathcal{N} = 1$ is convergent for high frequency Ω . This numerical result agrees well with the previous demonstration.

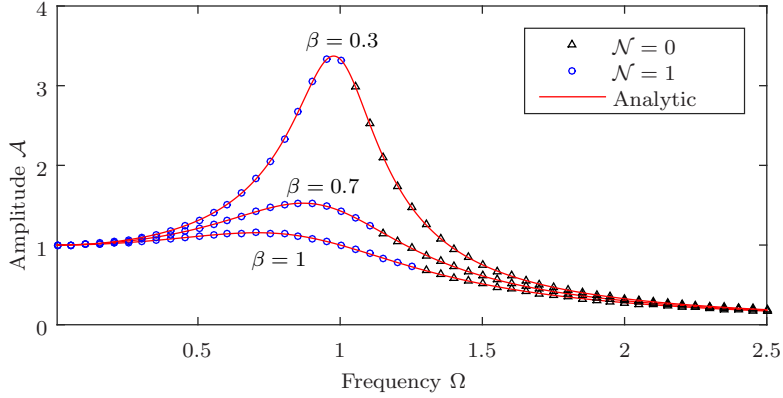


Figure 1: Forced linear oscillator by analytic and iteration methods

100 *4.2. Duffing oscillator*

Let's consider another example, a forced Duffing oscillator. This oscillator has many applications in physics and it can be described by

$$\ddot{u} + \beta\dot{u} + u + \varepsilon u^3 = A \cos \Omega t \quad (20)$$

When ε is small, the perturbation techniques [1, 21] can be applied for this oscillator. This technique demonstrates that the periodical solution depends on the frequency Ω by

$$\mathcal{A}^2 \left\{ \beta^2 \Omega^2 + \left(1 - \Omega^2 + \frac{3}{4} \varepsilon \mathcal{A}^2 \right)^2 \right\} = A^2, \quad \tan \vartheta = \frac{\beta \Omega}{1 - \omega^2 + \frac{3}{4} \varepsilon \mathcal{A}^2} \quad (21)$$

where $\mathcal{A} = \sqrt{q_1^2 + p_1^2}$ is the amplitude and $\tan \vartheta = p_1/q_1$ is the phase of the first harmonic.

Figure 2 shows the numerical results with different \mathcal{N} for a forced Duffing oscillator with parameters $\omega = 1$, $\beta = 0.1$, $\varepsilon = 0.01$ and $A = 1$. In this example,

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105 we take the number of harmonics $N = 7$ et the number of iteration $K = 200$
 110 for all frequencies Ω . Here, the schema is considered to converge when the
 111 amplitude of the last iteration changes less than 1%. We see that each iteration
 112 schema converges in each frequency domain of Ω . Particularly, in the domain
 113 I, two schemas converges to two different solutions, and in domain II, different
 114 schemas converge to the same solution.

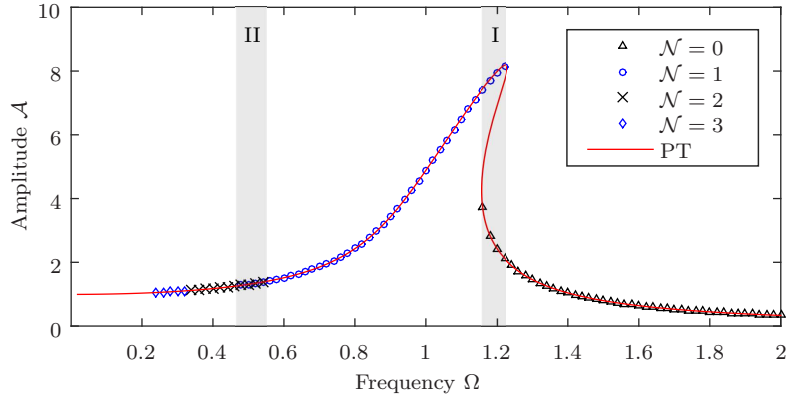


Figure 2: Forced Duffing oscillator by the perturbation technique (PT) and the iteration method. Parameter: $\omega = 1$, $\beta = 0.1$, $\varepsilon = 0.01$ and $A = 1$

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Figure 3 shows the results for the Duffing oscillator with different nonlinear parameter ε . We see that the schema $\mathcal{N} = 0$ converges for high frequency Ω and the schema $\mathcal{N} = 1$ converges for low frequency Ω . There is no schema of Table 1 converge to the unstable solution of the Duffing oscillator.

In order to estimate the convergence rate of the schemas, the numerical error of equation (20) is calculated by

$$\mathcal{O}(\varepsilon) = \max |\ddot{u} + \beta\dot{u} + u + \varepsilon u^3 - A \cos \Omega t|$$

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where $u(t)$ is the numerical result in each iteration. Figure 4 shows the error versus the number of iteration for the Duffing oscillator with $\varepsilon = 0.01$, $N = 10$ and $K = 1000$. We can see that the schemas converge in logarithmic scale of the number of iteration. Moreover, when the frequency Ω approaches the resonance frequency (green cycle markers), the convergence is relatively slow.

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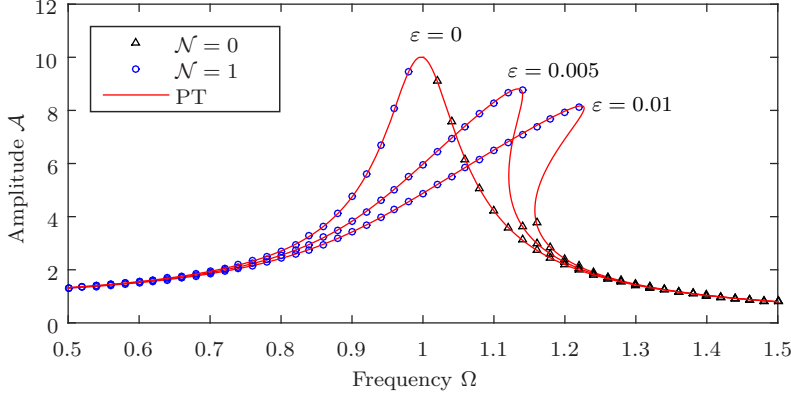


Figure 3: Forced Duffing oscillator by the perturbation technique (PT) and the iteration method

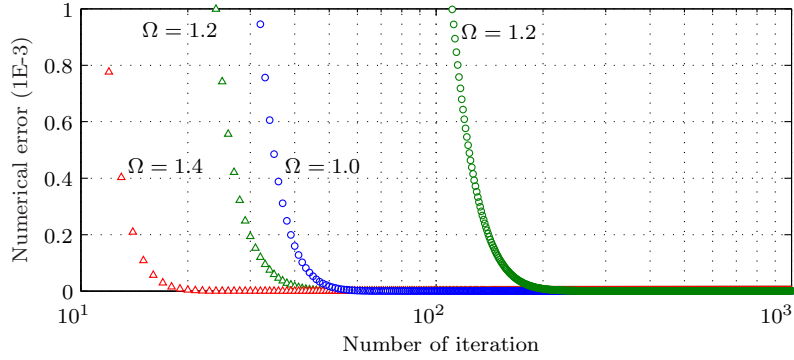


Figure 4: Numerical error in each iteration with the schema $\mathcal{N} = 0$ (triangle) and $\mathcal{N} = 1$ (cycle) for the Duffing oscillator

120 **5. Conclusion**

48 When the periodic solution of a dynamical system is decomposed into two
 49 parts corresponding low and high harmonics, we can propose an iteration schema
 50 with different formulations for the two parts. This decomposition can be built
 51 to adapt the system in term of convergence. The application for forced Duff-
 52 ing oscillators show that each schema converges in each range of the excitation
 53 frequency and we can reach different solutions by using different schema.

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9 **References**

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11 **References**

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13
14 [1] A. H. Nayfeh, D. T. Mook, Nonlinear Oscillations, Wiley Classics Library
15 130 Edition, 1995.
- 16
17 [2] R. Mickens, Comments on the method of harmonic balance, Journal of
18 Sound and Vibration 94 (3) (1984) 456–460.
- 19
20
21 [3] M. Urabe, Periodic solutions of differential systems, Galerkin’s procedure
22 and the method of averaging, Journal of Differential Equations 2 (3) (1966)
23 135 265–280.
- 24
25
26 [4] M. Urabe, A. Reiter, Numerical computation of nonlinear forced oscilla-
27 tions by Galerkin’s procedure, Journal of Mathematical Analysis and Ap-
28 plications 14 (1) (1966) 107–140.
- 29
30
31 [5] F. Ling, X. Wu, Fast galerkin method and its application to determine
32 periodic solutions of non-linear oscillators, International Journal of Non-
33 140 Linear Mechanics 22 (2) (1987) 89–98.
- 34
35
36 [6] R. Van Dooren, H. Janssen, Period doubling solutions in the Duffing os-
37 cillator: A Galerkin approach, Journal of Computational Physics 82 (1)
38 (1989) 161–171.
- 39
40
41 [7] R. Mickens, A generalization of the method of harmonic balance, Journal
42 of Sound and Vibration 111 (3) (1986) 515–518.
- 43
44 145 [8] R. Mickens, Iteration procedure for determining approximate solutions to
45 non-linear oscillator equations, Journal of Sound and Vibration 116 (1)
46 (1987) 185–187.
- 47
48
49 [9] R. E. Mickens, A generalized iteration procedure for calculating approxima-
50 tions to periodic solutions of truly nonlinear oscillators, Journal of Sound
51 and Vibration 287 (4-5) (2005) 1045–1051.
- 52
53 150
54
55
56
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58
59
60
61
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2
3
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5
6
7
8
9 [10] R. E. Mickens, Harmonic balance and iteration calculations of periodic
10 solutions to $\ddot{y} + y^{-1} = 0$, *Journal of Sound and Vibration* 306 (3-5) (2007)
11 968–972.
12 155
- 13
14 [11] K. C. Hall, J. P. Thomas, W. S. Clark, Computation of unsteady nonlinear
15 flows in cascades using a harmonic balance technique, *AIAA Journal* 40 (5)
16 (2002) 879–886.
17
18
19 [12] L. Liu, J. Thomas, E. Dowell, P. Attar, K. Hall, A comparison of classical
20 and high dimensional harmonic balance approaches for a Duffing oscillator,
21 160 *Journal of Computational Physics* 215 (1) (2006) 298–320.
22
23
24 [13] L. Liu, E. H. Dowell, K. C. Hall, A novel harmonic balance analysis for
25 the Van Der Pol oscillator, *International Journal of Non-Linear Mechanics*
26 42 (1) (2007) 2–12.
27
28
29 [14] A. LaBryer, P. Attar, A harmonic balance approach for large-scale prob-
30 165 lems in nonlinear structural dynamics, *Computers & Structures* 88 (17-18)
31 (2010) 1002–1014.
32
33
34 [15] B. Cochelin, C. Vergez, A high order purely frequency-based harmonic
35 balance formulation for continuation of periodic solutions, *Journal of Sound*
36 and *Vibration* 324 (1-2) (2009) 243–262.
37 170
38
39 [16] S. Karkar, B. Cochelin, C. Vergez, A high-order, purely frequency based
40 harmonic balance formulation for continuation of periodic solutions: The
41 case of non-polynomial nonlinearities, *Journal of Sound and Vibration*
42 332 (4) (2013) 968 – 977.
43
44
45 [17] S. Karkar, B. Cochelin, C. Vergez, A comparative study of the harmonic
46 balance method and the orthogonal collocation method on stiff nonlinear
47 systems, *Journal of Sound and Vibration* 333 (12) (2014) 2554–2567.
48 175
49
50 [18] P. Ju, X. Xue, Global residue harmonic balance method to periodic so-
51 lutions of a class of strongly nonlinear oscillators, *Applied Mathematical*
52 *Modelling* 38 (24) (2014) 6144–6152.
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61
62
63
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65

[19] P. Ju, X. Xue, Global residue harmonic balance method for large-amplitude oscillations of a nonlinear system, *Applied Mathematical Modelling* 39 (2) (2015) 449–454.

[20] P. Ju, Global residue harmonic balance method for HelmholtzDuffing oscillator, *Applied Mathematical Modelling* 39 (8) (2015) 2172–2179.

[21] A. H. Nayfeh, *Introduction to Perturbation techniques*, Wiley Classics Library Edition, 1993.

185