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Bifurcation tracking by Harmonic Balance Method for performance tuning of nonlinear dynamical systems

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Abstract

The aim of this paper is to provide an efficient frequency-domain method for bifurcation analysis of nonlinear dynamical systems. The proposed method consists in directly tracking the bifurcation points when a system parameter such as the excitation or nonlinearity level is varied. To this end, a so-called extended system comprising the equation of motion and an additional equation characterizing the bifurcation of interest is solved by means of the Harmonic Balance Method coupled with an arc-length continuation technique. In particular, an original extended system for the detection and tracking of Neimark-Sacker (secondary Hopf) bifurcations is introduced. By applying the methodology to a nonlinear energy sink and to a rotor-stator rubbing system, it is shown that the bifurcation tracking can be used to efficiently compute the boundaries of stability and/or dynamical regimes, i.e., safe operating zones.

Keywords: Harmonic balance method, Periodic solutions, Quasiperiodic solutions, Continuation, Bifurcation tracking, Limit point, Neimark-Sacker bifurcation, Floquet exponents, Nonlinear energy sink, Jeffcott rotor

1. Introduction

Industrial requirements in terms of security, cost reduction and increased performance push designers, manufacturers and operators to create more and more advanced technological equipment in which nonlinearities are now common. In this context, understanding and controlling nonlinear effects due to contact, large deflections, links or components such as bearings or friction dampers is an important issue. Resulting nonlinear systems can exhibit complex dynamical behaviours with specific features such as multi-solutions for a single value of the system parameters, amplitude or frequency jumps, internal resonances, period-doubling, quasi-periodic or chaotic motions [1–4]. However, for a given system, the systematic study of all these phenomena and their possible occurrence is generally out of reach because of the large number of parameters to be considered and the limited available computational resources. An overall understanding of the system’s dynamics can nevertheless be obtained through the computation of periodic solutions, forced response curves and associated bifurcations.

The literature comprises various numerical methods for the direct computation of periodic solutions which can be classified into two main categories, namely time domain and frequency domain approaches. The shooting method [5] and orthogonal collocation [6] which rely on solving a nonlinear boundary value problem are two popular time domain approaches. Orthogonal collocation is implemented for instance in AUTO [7] and MATCONT [8] softwares. In the frequency domain, the most commonly used method is certainly the harmonic balance method (HBM) which consists in approximating the unknown state variables by means of truncated Fourier series. Since nonlinearities cannot be directly computed in the frequency domain, the standard HBM is usually coupled with the alternating frequency-time (AFT) scheme [9] which computes the nonlinear terms in the time domain and subsequently their Fourier coefficients. The AFT scheme is very popular due to its easy implementation, its computational efficiency and its ability to handle almost any type of nonlinearities. Over the past decades, the HBM has been extended to quasi-periodic solutions

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is performed by means of minimally extended systems. In [47], Detroux et al. loads to imperfections [44–46]. In MATCONT, the continuation of codimension-1 bifurcations of dynamical systems standard extended systems. In a mechanical context, it was later used for studying the sensitivity of critical buckling of limit points of nonlinear equations having two parameters was first investigated by Jepson and Spence [43] with [19] while in [42] authors focus on Hopf bifurcations. MATCONT [8] software. A comprehensive review of the methods suitable for detecting bifurcations can be found in [32][40][41]. These minimally extended systems are implemented in AUTO [7] and LOCA [39] softwares. The computation of Hopf bifurcations by means of standard extended systems used for the computation of the bifurcations are then detailed in Section 4, with emphasis on computational fluid mechanics to detect instabilities when the Reynolds number reaches critical values [38]. Such standard extended systems originates from the work of Jepson [34]. Several variations and improvements have then been developed among others. This type of algorithm is frequently used in fluid mechanics to detect instabilities when the Reynolds number reaches critical values [38]. Such standard extended systems are implemented in AUTO [7] and LOCA [39] softwares. The computation of Hopf bifurcations by means of minimally extended systems is detailed in [32][40][41]. These minimally extended systems are implemented in MATCONT [8] software. A comprehensive review of the methods suitable for detecting bifurcations can be found in [19] while in [42] authors focus on Hopf bifurcations.

The numerical continuation of bifurcation points is much less addressed in the literature. The continuation of paths of limit points of nonlinear equations having two parameters was first investigated by Jepson and Spence [43] with standard extended systems. In a mechanical context, it was later used for studying the sensitivity of critical buckling loads to imperfections [44–46]. In MATCONT, the continuation of codimension-1 bifurcations of dynamical systems is performed by means of minimally extended systems. In [47], Detroux et al. combined this approach with the HBM for the tracking of limit point, branch point and Neimark-Sacker bifurcations of large-scale mechanical systems. In this paper, we combine HBM and standard extended systems. We already used this approach in [48] in the case of limit points. Here, this work is extended to all types of codimension-1 bifurcations. In particular, we build on the work of Griewank and Reddien [35] in order to propose an efficient algorithm for the computation and the tracking of Neimark-Sacker bifurcations.

The paper is organized as follows. The formulation of the harmonic balance method for the continuation of periodic solutions is presented in Section 2. The stability analysis and the characterization of the bifurcations are based on the Floquet exponents obtained from a quadratic eigenvalue problem as described in Section 3. The extended systems used for the computation of the bifurcations are then detailed in Section 4, with emphasis on computational
issues such as the efficient calculation of the derivatives involved in the Newton-Raphson iterations. The direct tracking of these bifurcations, i.e., the continuation of bifurcation curves is addressed in Section 5. The performance of the proposed approach is demonstrated in Section 6 on two nonlinear dynamical problems: a nonlinear vibration absorber and a nonlinear Jeffcott rotor. Finally, conclusions are drawn in the last section.

2. Equilibrium path

2.1. Harmonic Balance Method

A forced nonlinear dynamical system with \( n \) degrees of freedom (DOFs) governed by the following set of equations of motion is considered

\[
r(x, \omega, t) = M\ddot{x}(t) + C\dot{x}(t) + Kx(t) + f_{nl}(x, \dot{x}) - p(\omega, t) = 0
\]

with \( x(t) \) the displacement vector containing the \( n \) DOFs, \( M, C, K \) the generalized mass, damping and stiffness matrices, \( f_{nl} \) the vector of nonlinear forces, \( p(\omega, t) \) the periodic excitation forces and \( \omega \) the excitation frequency.

Harmonic balance method is used for its efficiency compared to time integration to predict periodic solutions. Assuming that the harmonic response has the same period \( \tau = 2\pi/\omega \) as the excitation, the nonlinear forces and excitation forces can be represented as Fourier series up to order \( H \)

\[
x(t) = X^0 + \sum_{k=1}^{H} X^k \cos(k\omega t) + X^k \sin(k\omega t)
\]

\[
f_{nl}(x, \dot{x}) = F^0 + \sum_{k=1}^{H} F^k \cos(k\omega t) + F^k \sin(k\omega t)
\]

\[
p(\omega, t) = P^0 + \sum_{k=1}^{H} P^k \cos(k\omega t) + P^k \sin(k\omega t)
\]

where

\[
X = [X^0_T, X^1_c, X^1_s, \ldots, X^H_c, X^H_s]^T
\]

\[
F_{nl} = [F^0_T, F^1_c, F^1_s, \ldots, F^H_c, F^H_s]^T
\]

\[
P = [P^0_T, P^1_c, P^1_s, \ldots, P^H_c, P^H_s]^T
\]

are vectors of Fourier coefficients of size \( L = n \times (2H + 1) \). Equation (2) can be rewritten in the compact form

\[
x(t) = (T(\omega t) \otimes I_n)X
\]

\[
f_{nl}(x, \dot{x}) = (T(\omega t) \otimes I_n)F_{nl}
\]

\[
p(\omega, t) = (T(\omega t) \otimes I_n)P
\]

where the linear operator \( T \) stands for the inverse Fourier transform and is made of trigonometric functions

\[
T(\omega t) = [1 \ \cos(\omega t) \ \sin(\omega t) \ \ldots \ \cos(H\omega t) \ \sin(H\omega t)]
\]

\( I_n \) is the \( n \times n \) identity matrix and \( \otimes \) is the Kronecker tensor product. Similarly, introducing the derivative operator

\[
\nabla = \text{diag}(0, \nabla_1, \ldots, \nabla_j, \ldots, \nabla_R) \quad \text{with} \quad \nabla_j = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}
\]

the velocity and acceleration vectors can be written as follows

\[
\dot{x}(t) = \omega(T(\omega t) \otimes I_n)(\nabla \otimes I_n)X = \omega[(T(\omega t)\nabla) \otimes I_n]X
\]

\[
\ddot{x}(t) = \omega^2(T(\omega t) \otimes I_n)(\nabla^2 \otimes I_n)X = \omega^2[(T(\omega t)\nabla^2) \otimes I_n]X
\]
A Galerkin procedure is then applied to the equations of motion, which consists in projecting Eq.(1) on the trigonometric basis $T(\omega t)$ with respect to the scalar product

$$\langle f, g \rangle = \frac{2}{\tau} \int_0^\tau f \cdot g \, dt$$ (8)

By introducing Eqs.(4) and (7) into the resulting equations and using the orthogonality property $\langle T(\omega t), T(\omega t) \rangle = I_{2H+1}$, the nonlinear system of $n$ equations (1) in the time domain is transformed into a nonlinear algebraic system of dimension $L$ in the frequency domain

$$R(X, \omega) = Z(\omega)X + F_{nl}(X) - P = 0$$ (9)

where

$$Z(\omega) = \omega^2 \nabla^2 \otimes M + \omega \nabla \otimes C + I_{2H+1} \otimes K = \text{diag}(K, Z_1, \ldots, Z_H)$$ (10)

$$Z_j = \begin{bmatrix} K - j^2 \omega^2 M - \omega C & \omega C \\ -\omega C & K - j^2 \omega^2 M \end{bmatrix}$$ (11)

An incremental-iterative Newton-Raphson procedure is used to obtain solutions of Eq.(9), with corrections $\delta X$ given by

$$R^k \delta X = -R^k$$ (12)

$$X^{k+1} = X^k + \delta X$$ (13)

where $R_X$ stands for the derivative of $R$ with respect to $X$ and the superscript $k$ indicates an evaluation with updated variables at iteration $k$, i.e.

$$R^k = R(X^k) \quad R^k_X = \frac{\partial R}{\partial X} \bigg|_{X=X^k}$$ (14)

2.2. Continuation technique and path-following

Nonlinear systems often have several possible responses for a given excitation frequency $\omega$. The pseudo-arc length continuation method [49] combined with the above-mentioned algorithm permits following the solution branch beyond limit points in order to obtain both stable and unstable solutions of the response curve. It is based on tangent prediction and orthogonal corrections [19]. For this purpose, not only $X$ but also $\omega$ is considered as an unknown. Once a starting point $(X^0, \omega^0)$ on the solution curve has been obtained by solving Eq.(12), a tangent vector $t = (\Delta X, \Delta \omega)$ is obtained from

$$\begin{bmatrix} R_X \bigg|_{X=X^0} \\ R_\omega \bigg|_{X=X^0} \end{bmatrix} \begin{bmatrix} \Delta X \\ \Delta \omega \end{bmatrix} = 0$$ (15)

where $R_\omega = \partial R / \partial \omega$. A normalization condition $\|t\| = \Delta X^2 + \Delta \omega^2 = 1$ is added to make the tangent vector unitary and the prediction step gives a solution at distance $\Delta s$ along direction $t$

$$\begin{bmatrix} X^1 \\ \omega^1 \end{bmatrix} = \begin{bmatrix} X^0 \\ \omega^0 \end{bmatrix} + \Delta s \, t$$ (16)

Then, this prediction is corrected iteratively in the direction orthogonal to $t$ until the convergence criterion $\|R^k\| \leq \varepsilon$ is satisfied, with $\varepsilon$ a user-defined accuracy. The corrections $\delta X^{k+1}$ and $\delta \omega^{k+1}$ are given by the system of $L + 1$ equations

$$\begin{bmatrix} R^k_X \\ R^k_\omega \end{bmatrix} \begin{bmatrix} \delta X^{k+1} \\ \delta \omega^{k+1} \end{bmatrix} = \begin{bmatrix} -R^k \\ 0 \end{bmatrix}$$ (17)

and the solution at iteration $k + 1$ is obtained with

$$X^{k+1} = X^k + \delta X^{k+1}$$

$$\omega^{k+1} = \omega^k + \delta \omega^{k+1}$$ (18)

Finally, an adaptive step-length algorithm [19] based on the number of iterations in the corrector step is used to ensure robust continuation.
2.3. Computation of nonlinear terms and derivatives

Nonlinear forces are usually much easier to evaluate in the time domain than in the frequency domain. Therefore, the Fourier coefficients of nonlinear efforts $F_{nl}$ and their derivative $\frac{\partial F_{nl}}{\partial \mathbf{X}}$ involved in the Newton-Raphson iterations are obtained by Alternating Frequency-Time (AFT) method [9]. The AFT algorithm uses discrete Fourier transforms (DFT) to compute the nonlinear forces in the time domain and then switches back to the frequency domain

$$
X \xrightarrow{DFT^{-1}} \mathbf{x}(t), \mathbf{\dot{x}}(t) \xrightarrow{DFT} \mathbf{F}_{nl}(X)
$$

Defining $N$ uniformly spaced time samples $t_i = i \Delta t, i = 1 \ldots N$, such that $\Delta t = \tau/N$ with $N \geq 2H + 1$ and the corresponding vectors of $N$ time samples of the displacements and nonlinear forces

$$
\begin{align*}
\mathbf{x} &= [x(t_1), \ldots, x(t_N)]^T \\
\mathbf{f}_{nl} &= [f_{nl}(t_1), \ldots, f_{nl}(t_N)]^T
\end{align*}
$$

and using Eq.(4) yields the following inverse-DFT relations between the vectors of time samples and the Fourier coefficients [50]

$$
\mathbf{x} = [T(\omega t_1) \otimes \mathbf{I}_n, \ldots, T(\omega t_N) \otimes \mathbf{I}_n]^T X = (\Gamma \otimes \mathbf{I}_n)X
$$

$$
\mathbf{x} = [T(\omega t_1) \otimes \mathbf{I}_n, \ldots, T(\omega t_N) \otimes \mathbf{I}_n] (\Gamma \otimes \mathbf{I}_n)X = \omega(\Gamma \otimes \mathbf{I}_n)(\nabla \otimes \mathbf{I}_n)X = \omega[\nabla(\Gamma \otimes \mathbf{I}_n)]X
$$

Once $\mathbf{f}_{nl}$ has been computed in the time domain using $\mathbf{x}$ and $\mathbf{\dot{x}}$, the following DFT relation is used to go back to the frequency domain

$$
\mathbf{f}_{nl} = (\Gamma \otimes \mathbf{I}_n)^{-1} \mathbf{f}_{nl} = (\Gamma^{-1} \otimes \mathbf{I}_n)\mathbf{f}_{nl}
$$

Remarkably, matrices $\Gamma$ and $\Gamma^{-1}$ do not depend on $\omega$ and thus can be conveniently written as follows after introducing $\theta_i = \omega t_i = 2\pi i/N$

$$
\begin{align*}
\Gamma &= \begin{bmatrix}
1 & \cos \theta_1 & \sin \theta_1 & \ldots & \cos H\theta_1 & \sin H\theta_1 \\
\vdots & \vdots & \vdots & \ldots & \vdots & \vdots \\
1 & \cos \theta_N & \sin \theta_N & \ldots & \cos H\theta_N & \sin H\theta_N \\
\end{bmatrix} \\
\Gamma^{-1} &= \frac{1}{N} \begin{bmatrix}
1 & \ldots & 1 \\
2 \cos \theta_1 & \ldots & 2 \cos \theta_N \\
2 \sin \theta_1 & \ldots & 2 \sin \theta_N \\
\vdots & \vdots & \vdots \\
2 \cos H\theta_1 & \ldots & 2 \cos H\theta_N \\
2 \sin H\theta_1 & \ldots & 2 \sin H\theta_N \\
\end{bmatrix}
\end{align*}
$$

Using the chain rule, the derivative of $\mathbf{F}_{nl}$ can then be obtained

$$
\frac{\partial \mathbf{F}_{nl}}{\partial \mathbf{X}} = \frac{\partial \mathbf{F}_{nl}}{\partial \mathbf{f}_{nl}} \frac{\partial \mathbf{f}_{nl}}{\partial \mathbf{\dot{x}}} \frac{\partial \mathbf{\dot{x}}}{\partial \mathbf{x}} + \frac{\partial \mathbf{F}_{nl}}{\partial \mathbf{f}_{nl}} \frac{\partial \mathbf{f}_{nl}}{\partial \mathbf{x}} \frac{\partial \mathbf{X}}{\partial \mathbf{\dot{x}}} = (\Gamma^{-1} \otimes \mathbf{I}_n) \frac{\partial \mathbf{f}_{nl}}{\partial \mathbf{\dot{x}}} (\Gamma \otimes \mathbf{I}_n) + (\Gamma^{-1} \otimes \mathbf{I}_n) \frac{\partial \mathbf{f}_{nl}}{\partial \mathbf{x}} \omega[\nabla(\Gamma \otimes \mathbf{I}_n)]
$$

with the $nN \times nN$ block-diagonal matrices of time samples of $\mathbf{f}_{nl}$ derivatives

$$
\begin{align*}
\frac{\partial \mathbf{f}_{nl}}{\partial \mathbf{\dot{x}}} &= \text{diagblk} \left( \frac{\partial \mathbf{f}_{nl}}{\partial \mathbf{x}} \mid_{t=t_1}, \ldots, \frac{\partial \mathbf{f}_{nl}}{\partial \mathbf{x}} \mid_{t=t_N} \right) \\
\frac{\partial \mathbf{f}_{nl}}{\partial \mathbf{x}} &= \text{diagblk} \left( \frac{\partial \mathbf{f}_{nl}}{\partial \mathbf{\dot{x}}} \mid_{t=t_1}, \ldots, \frac{\partial \mathbf{f}_{nl}}{\partial \mathbf{\dot{x}}} \mid_{t=t_N} \right)
\end{align*}
$$

In the case of systems with distinct states, the differentiation of the nonlinear force $\mathbf{F}_{nl}$ requires a specific treatment as detailed in [16].
The Jacobian $R_X$ is eventually given by

$$R_X = Z(\omega) + \frac{\partial F_{nl}}{\partial X}$$  \hspace{1cm} (27)

The expression of $R_\omega$ is immediate from Eqs.(9) and (10)

$$R_\omega = Z_\omega X$$  \hspace{1cm} (28)

where

$$Z_\omega = \frac{\partial Z}{\partial \omega} = 2\omega \nabla^2 \otimes M + \nabla \otimes C$$  \hspace{1cm} (29)

3. Stability analysis and bifurcation points

The continuation technique permits to find several solutions on the response curve for one given excitation. However, some of them are not stable and cannot be experimentally reproduced. In addition, only periodic solutions are found with the HBM described in the previous section. As a result, stability analysis and detection of bifurcations indicating changes of dynamical regime are essential tools in numerical simulations.

Stability of solutions can be examined by means of Hill’s method which is variant of Floquet theory for frequency-domain methods such as HBM [22, 23]. Hill’s method consists in perturbing the equations of motion (1) around a periodic solution and applying the same Galerkin procedure as in Section 2.1 for HBM. The following quadratic eigenvalue problem is obtained

$$(R_X + \Lambda \Delta_1 + \Lambda^2 \Delta_2) \phi = 0$$  \hspace{1cm} (30)

where $\phi = \phi_1 + i \phi_2$ are complex eigenvectors, $R_X$ is the Jacobian defined by Eq.(27) and

$$\Delta_1 = 2\omega \nabla \otimes M + I_{2H+1} \otimes C = \text{diag} \left( C, \left[ \begin{array}{cc} 2\omega M & 2\omega M \\ -2\omega M & C \\ \vdots & \vdots \\ -2H\omega M & C \end{array} \right] \right)$$  \hspace{1cm} (31)

$$\Delta_2 = I_{2H+1} \otimes M$$  \hspace{1cm} (32)

It should be noted that $2L = 2n(2H + 1)$ complex eigenvalues $\Lambda$ are obtained from Eq.(30), of which only the $2n$ ones with the smallest imaginary part are expected to have a physical meaning and correspond to the Floquet exponents [51] denoted $\lambda_i$, $i = 1 \ldots 2n$ in the following.

By definition, a singular point appears when a Floquet exponent $\lambda$ is null (see Fig.1), i.e. when the determinant $\varphi = \text{det}(R_X)$ vanishes. The indicator $\varphi$ is thus monitored during the continuation of the response curve and a change of sign of $\varphi$ between two consecutive points indicates the presence of a limit or branch point. The type of solution can be classified as follows [19, 32]

- Regular point if $\varphi = \text{det}(R_X) \neq 0$ and $R_X^T \phi \neq 0$
- Limit point (LP) / Fold bifurcation if $\varphi = \text{det}(R_X) = 0$ and $R_X^T \phi \neq 0$
- Branch point (BP) if $\varphi = \text{det}(R_X) = 0$ and $R_X^T \phi = 0$

$$\text{Im}$$

$$\text{Re}$$

Figure 1: Floquet exponents crossing the imaginary axis on the complex plane indicate a bifurcation
where \( \phi \) is the eigenvector associated with the null eigenvalue \( \Lambda = 0 \) of \( R_X \). A Neimark-Sacker (NS) or secondary Hopf bifurcation indicates a transition from periodic to quasi-periodic regime (see Fig. 2) for solutions of the time-domain equation (1). Its analogue in the framework of the frequency-domain HBM is a Hopf bifurcation which indicates a transition from a fixed point (solution with constant Fourier coefficients) to a limit cycle (solution with periodic Fourier coefficients). Considering this equivalence, both denominations will be used indifferently in the following. A NS bifurcation occurs when a complex conjugate pair of Floquet exponents crosses the imaginary axis of the complex plane with \( \lambda = \pm i \kappa, \kappa \neq \pi / \tau \) (see Fig. 1). The presence of a NS bifurcation along the equilibrium curve can thus be detected by monitoring the evolution of the Floquet exponents. Indicators which vanish at a NS bifurcation are available [19, 32, 40]

\[
\varphi_{NS1} = \prod_{1 \leq j < i \leq 2n} (\lambda_i + \lambda_j) \\
\varphi_{NS2} = \text{det}(2A \otimes I_{2n})
\]

where \( A \) is the diagonal matrix of the \( 2n \) Floquet exponents \( A = \text{diag}(\lambda_1, \ldots, \lambda_{2n}) \) and \( \otimes \) stands for the bialternate product. These two indicators are equivalent because matrix \( 2A \otimes I_{2n} \) has eigenvalues \( \lambda_i + \lambda_j \). However, one has to be careful when using them since they vanish not only for NS bifurcations but also for a pair of opposite real Floquet exponents \( \lambda = \pm \kappa \) indicating a neutral saddle point.

4. Localization of bifurcation points

As stated in the introduction, two approaches exist for the precise computation of bifurcation points. The first one relies on so-called standard extended systems and consists in introducing one or more additional equations characterizing the bifurcation [19, 26]. The second approach relies on bordering techniques and minimally extended systems in which only one scalar function is added [32, 40, 47]. The approach based on standard extended systems is used in the present paper. The main motivation for this choice is the ease of implementation since the additional equations involved in standard extended systems have the same form and thus involve the same derivatives whatever the type of bifurcation, as shown in the next sections. The counterpart is an increase in the size of the problem, as compared to minimally extended systems, but the extra computational cost can be reduced with the use of a block elimination algorithm [52].

The following procedure is used to locate bifurcation points. When a change of sign of indicators \( \varphi \) or \( \varphi_{NS} \) is detected between two consecutive solution points, the point with the smallest absolute value of the indicator is used as a starting point \((X^0, \omega^0)\) for the fully extended system.

4.1. Localization of limit points (LP) / Fold bifurcations

To locate limit points precisely, it is computationally more efficient to use the equation \( R_X y = 0 \), obtained by substituting \( \Lambda = 0 \) into (30), rather than the test function \( \varphi = \text{det}(R_X) = 0 \) for the additional equation of the extended
system. The resulting $2L + 1$ extended system for localizing LPs takes the form

$$G(Y) = \begin{pmatrix} R(X, \omega) \\ R_X \phi \\ \phi_1 \end{pmatrix} - 0_{2L+1} \tag{35}$$

with $Y = (X, \phi, \omega)$. The first equation defines the equilibrium path, the second one characterizes the limits points and the last one normalizes the eigenvector $\phi$. This extended system was first introduced by Moore and Spence [26]. System (35) can be solved by a Newton-Raphson method, with corrections at iteration $k$ given by

$$G_Y(Y^k) \delta Y = -G(Y^k) \tag{36}$$
$$Y^{k+1} = Y^k + \delta Y \tag{37}$$

with $\delta Y = (\delta X, \delta \phi, \delta \omega)$. Eq.(36) can be written explicitly as

$$\begin{bmatrix} R^k_X \\ (R_X \phi)^k \\ 0_{L \times L} \\ R^k_\omega \\ (R_X \phi)^k \\ 0_L \end{bmatrix} \begin{bmatrix} 0_{L \times L} \\ R^k_\omega \\ (R_X \phi)^k \\ 0_{L} \\ 2\phi^T \delta \phi \\ 0 \end{bmatrix} \begin{bmatrix} \delta X \\ \delta \phi \end{bmatrix} = - \begin{bmatrix} R^k_\omega \\ (R_X \phi)^k \end{bmatrix} \begin{bmatrix} \phi^T \delta \phi - 1 \end{bmatrix} \tag{38}$$

In practice, the eigenvector corresponding to the smallest eigenvalue of $R_X(X^0, \omega^0)$ can be used as a starting value $\phi^0$ for $\phi$. The $2L + 1$ extended system (38) is regular at limit points and can be inverted. If $L$ is large, a block elimination algorithm [52] can be used in order to deal with sub-systems of size $L$ only, involving $R_X$, and thus reduce the computational work. In this case, one has to deal with $R_X$ becoming singular when approaching the limit point [28, 53].

4.2. Localization of branch points (BP)

Based on the classification (33), the following additional equation in introduced in order to discriminate branch points from limit points

$$R^T \phi = 0 \tag{39}$$

Contrary to limit points, system (38) is singular at branch points. In order to avoid the singularity when approaching branch points, a penalty term $\gamma e_j$ is introduced where $e_j$ is a unit vector with $j$-th component equal to 1 and $\gamma$ is an auxiliary variable [53]. In practice, the initial value initial value for $\gamma$ is assumed to be 0 and the eigenvector corresponding to the smallest eigenvalue of $R_X(X^0, \omega^0)$ can be used as a starting value $\phi^0$ for $\phi$. Consequently, the $2L + 2$ extended system to be solved during the Newton-Raphson procedure is given by

$$\begin{bmatrix} R^k_X \\ (R_X \phi)^k \\ 0_{L \times L} \\ R^k_\omega \\ (R_X \phi)^k \\ 0_L \end{bmatrix} \begin{bmatrix} 0_{L \times L} \\ R^k_\omega \\ (R_X \phi)^k \\ 0_{L} \\ 2\phi^T \delta \phi \\ 0 \end{bmatrix} \begin{bmatrix} \delta X \\ \delta \phi \end{bmatrix} = - \begin{bmatrix} R^k_\omega + \gamma e_j \\ (R_X \phi)^k \end{bmatrix} \begin{bmatrix} \phi^T \delta \phi - 1 \end{bmatrix} \tag{40}$$

Again, a block elimination algorithm can be used in order to solve sub-systems of size $L$ involving $R_X$ only, with a particular attention on $R_X$ becoming progressively ill-conditioned [30].

4.3. Localization of Neimark-Sacker (NS) bifurcations

The original extended system presented here takes inspiration from the approach of Griewank and Reddien [35] which has been adapted to work within the framework of the HBM.

By substituting $\Lambda = \pm i\kappa$ and $\phi = \phi_1 \pm i \phi_2$ into (30) and identifying real and imaginary parts, two equations characterizing NS bifurcations are obtained. Along with equilibrium and normalization equations, they provide the $3L + 2$ extended system for locating NS bifurcations

$$K(X, \phi, \phi_1, \phi_2, \kappa, \omega) = \begin{pmatrix} R(X, \omega) \\ R_X \phi_1 - \kappa \Delta_1 \phi_2 - \kappa^2 \Delta_2 \phi_1 \\ R_X \phi_2 + \kappa \Delta_1 \phi_1 - \kappa^2 \Delta_2 \phi_2 \\ \phi_1 \phi_1 - 1 \end{pmatrix} = 0_{3L+2} \tag{41}$$
where \( q \) a constant vector with non zero projection on \( \text{span}[\phi_1, \phi_2] \). It is worth noting that other normalizations are possible, which can affect the algorithm behaviour. For instance, replacing \( q^T \phi_1 = 0 \) and \( \phi_1^T \phi_1 = 1 \) by \( q^T \phi_1 = 0 \) and \( q^T \phi_2 = 1 \) in (41) leads to other solutions. In this case, for \( \kappa = 0 \), one has \( \phi_1 = 0 \) and the augmented system is reduced to (35) and therefore limit points are obtained [35][37]. Obviously, these normalizations should be avoided if only NS bifurcations are tracked, but they can be of interest for switching from a branch of LPs to a branch of NS bifurcations.

Once a starting point \((X_0, \omega^0)\) on the equilibrium path in the neighbourhood of the NS bifurcation is available, the eigenvector corresponding to the complex eigenvalue \( \Lambda = \imath \kappa \) of \( R_X(X_0, \omega^0) \) can be used as a starting value for \( \phi = \phi_1 + \imath \phi_2 \). This initial solution is then corrected by means of Newton-Raphson iterations resulting from the linearization of Eq.(41)

\[
\begin{bmatrix}
R^k_X & 0_{L \times L} & 0_{L \times L} & 0 & 0 & 0 & R^k_w \\
(R_X \phi_1^k)_{X^k} & R^k_X - (\kappa^2)^2 \Delta_2 & -\kappa^2 \Delta_2^k & -\Delta_2^k \phi_1^k & -2\kappa^2 \Delta_2 \phi_2^k & (R_X \phi_1^k)_{X_0^k} - \kappa^2 (\Lambda_1 \phi_1^k)_{X_0^k} \\
(R_X \phi_2^k)_{X^k} & \kappa^2 \Delta_2^k & R^k_X - (\kappa^2)^2 \Delta_2 & +\Delta_2^k \phi_1^k & -2\kappa^2 \Delta_2 \phi_1^k & (R_X \phi_2^k)_{X_0^k} + \kappa^2 (\Lambda_1 \phi_1^k)_{X_0^k} \\
0^T & q^T & 0^T & 0 & 0 & 0 & 0 \\
0^T & 2\phi_1^T & 0^T & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\begin{bmatrix}
\delta X \\
\delta \phi_1 \\
\delta \phi_2 \\
\delta \kappa \\
\delta \omega \\
\end{bmatrix}
\]

\[
= - \begin{bmatrix}
R^k_X & 0_{L \times L} & 0_{L \times L} & 0 & 0 & 0 & R^k_w \\
(R_X \phi_1^k)_{X^k} & R^k_X - (\kappa^2)^2 \Delta_2 & -\kappa^2 \Delta_2^k & -\Delta_2^k \phi_1^k & -2\kappa^2 \Delta_2 \phi_2^k & (R_X \phi_1^k)_{X_0^k} - \kappa^2 (\Lambda_1 \phi_1^k)_{X_0^k} \\
(R_X \phi_2^k)_{X^k} & \kappa^2 \Delta_2^k & R^k_X - (\kappa^2)^2 \Delta_2 & +\Delta_2^k \phi_1^k & -2\kappa^2 \Delta_2 \phi_1^k & (R_X \phi_2^k)_{X_0^k} + \kappa^2 (\Lambda_1 \phi_1^k)_{X_0^k} \\
0^T & q^T & 0^T & 0 & 0 & 0 & 0 \\
0^T & 2\phi_1^T & 0^T & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\begin{bmatrix}
\delta X \\
\delta \phi_1 \\
\delta \phi_2 \\
\delta \kappa \\
\delta \omega \\
\end{bmatrix}
\]

Again, a block elimination algorithm can be used in order to solve sub-systems of size \( L \) only. This time, no particular procedure is necessary for \( R_X \) since it is non-singular at NS bifurcations.

4.4. Computation of the additional derivatives involved the extended systems

Expressions for the derivatives \( R_X \) and \( R_w \) are given in Eqs. (27) and (28). Since the vector of Fourier coefficients \( \phi \) does not depend on \( \omega \), the derivative \((R_X \phi)_w\) is given by

\[
(R_X \phi)_w = (R_X)_w \phi = Z_\omega \phi
\]

with \( Z_\omega \) calculated with Eq.(29). Similarly, the derivatives involving \( \Lambda_1 \) are obtained from Eq.(31) as follows

\[
(\Lambda_1 \phi)_w = (\Lambda_1)_w \phi = 2(\nabla \otimes M) \phi
\]

The derivative \((R_X \phi)_X\) can be computed by means of the AFT method much in the same way as for \( \partial \bar{\mathbf{f}}_w / \partial \bar{X} \) in Section 2.3

\[
(R_X \phi)_X = (\Gamma^{-1} \otimes I_n) \frac{\partial \bar{r}_X \mathbf{\phi}}{\partial \bar{X}} (\Gamma \otimes I_n)
\]

with the \( nN \times nN \) block-diagonal matrix of time samples

\[
\frac{\partial \bar{r}_X \mathbf{\phi}}{\partial \bar{X}} = \text{diagblk} \left( \frac{\partial r_X \mathbf{\phi}}{\partial \bar{X}} |_{t=1} , \ldots , \frac{\partial r_X \mathbf{\phi}}{\partial \bar{X}} |_{t=N} \right)
\]

(46)

where \( r_X \) is the derivative of the equilibrium residual (1) in the time domain and the eigenmode \( \varphi \) in the time domain can be obtained from

\[
\hat{\varphi} = [\varphi(t_1), \ldots , \varphi(t_N)]^T = (\Gamma \otimes I_n) \varphi
\]

(47)

\((r_X \varphi)_t\) can be obtained analytically in very simple cases only. For complicated systems or systems with many DOFs, it can be approximated by finite differences [27]

\[
(r_X \varphi)_t \approx \frac{\partial r_X \varphi}{\partial x} \approx \frac{1}{\Delta x} [r_X(x + \Delta x \varphi) - r_X(x)]
\]

(48)
Similarly, \((R_X\phi)_X\) can also be computed directly in the frequency domain as
\[
(R_X\phi)_X \approx \frac{1}{\varepsilon_X} [R_X(X + \varepsilon_X\phi) - R_X(X)]
\]  (49)

In Eqs. (48) and (49), the proper scaling of the perturbations \(\varepsilon_\phi\) and \(\varepsilon_X\phi\) with respect to \(x\) and \(X\) is essential to ensure good accuracy and robustness of the numerical differentiation. This is accomplished by means of the following formulas in which a suitable value for \(\eta\) has to be chosen. Using \(\eta = 10^{-6}\) has been found to provide good results for a large range of applications.
\[
\varepsilon_x = \eta \left(\frac{\|x\|}{\|\phi\|} + \eta\right) \quad \varepsilon_X = \eta \left(\frac{\|X\|}{\|\phi\|} + \eta\right)
\]  (50)

5. Parametric continuation of bifurcation points

The following computational procedure is used to follow a branch of bifurcation points:

1. For a fixed value \(\alpha_0\) of a system parameter, nonlinearity or excitation level for instance, follow the equilibrium path (see Section 2.2) until a bifurcation point \((X^0,\omega^0,\alpha^0)\) is encountered and precisely detected (Section 4), which serves as a starting point.

2. Free \(\alpha\) and follow the path of bifurcations by a continuation method.

The last step is carried out by adding a pseudo-arc length constraint equation to one of the extended systems (38)(40)(42) depending on the type on bifurcation to be followed. As in Section 2.2, a tangent vector \(t = (\Delta X, \Delta \omega, \Delta \alpha)\) is first computed, then the next bifurcation point if obtained after Newton-Raphson corrections orthogonal to \(t\).

In the case of LP tracking, these corrections are solutions of the 2\(L + 2\) extended system

\[
\begin{pmatrix}
R_X^k & 0_{L\times L} & R_{\phi X}^k & R_{\phi \alpha}^k & \frac{\partial X}{\partial \phi} & 0 \\
0_{L\times L} & 2\phi^T & 0 & 0 & 0 & 0 \\
\Delta X^T & 0_{L\times L} & \Delta \omega & \Delta \alpha & \frac{\partial \phi}{\partial \alpha} & \frac{\partial \phi}{\partial \omega}
\end{pmatrix}
\begin{pmatrix}
\phi_k \\
\delta \phi \\
\delta \omega \\
\delta \alpha
\end{pmatrix} = \begin{pmatrix}
R^k \\
R_{\phi X}^k \\
R_{\phi \alpha}^k
\end{pmatrix}
\]  (51)

and the two additional derivatives \(R_\alpha\) and \((R_X\phi)_\alpha\) are given by

\[
R_\alpha = \frac{\partial Z}{\partial \alpha} X + \frac{\partial F_{nl}}{\partial \alpha} - \frac{\partial P}{\partial \alpha} (R_X\phi)_\alpha = \left(\frac{\partial Z}{\partial \alpha} + \frac{\partial^2 F_{nl}}{\partial X \partial \alpha}\right) \phi
\]  (52)

Analytical expressions for these two derivatives depend on the system parameter \(\alpha\) under consideration and vary with each case. In order to compute them conveniently for any system parameter, finite differences can be used with \(\varepsilon_\alpha = \eta|\alpha| + \eta\) and \(\eta = 10^{-6}\)

\[
R_\alpha(X, \omega, \alpha) = \frac{1}{\varepsilon_\alpha} [R(X, \omega, \alpha + \varepsilon_\alpha) - R(X, \omega, \alpha)]
\]  (53)

\[
(R_X\phi)_\alpha(X, \omega, \alpha) = \frac{1}{\varepsilon_\alpha} [R_X(X, \omega, \alpha + \varepsilon_\alpha) - R_X(X, \omega, \alpha)]\phi
\]  (54)

Similarly, in the case of BP tracking, Newton-Raphson corrections are solutions of the 2\(L + 3\) extended system

\[
\begin{pmatrix}
R_X^k & 0_{L\times L} & R_{\phi X}^k & R_{\phi \alpha}^k & e_\gamma & e_j & 0 & 0 & 0 & e_j \\
0_{L\times L} & 2\phi^T & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\Delta X^T & 0_{L\times L} & \Delta \omega & \Delta \alpha & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{pmatrix}
\begin{pmatrix}
\frac{\partial X}{\partial \phi} \\
\frac{\partial \phi}{\partial \omega} \\
\frac{\partial \phi}{\partial \alpha}
\end{pmatrix} = \begin{pmatrix}
R^k + \gamma e_j \\
R_{\phi X}^k \\
R_{\phi \alpha}^k
\end{pmatrix}
\]  (55)
Finally, in the case of NS tracking, Newton-Raphson corrections are solutions of the $3L + 3$ extended system

$$
\begin{bmatrix}
R^*_{X_l} & 0_{L\times L} & 0_{L\times L} & 0_L & R^*_{\omega x} & R^*_{\omega y} \\
(R_X\phi_1)_T & R^*_{X_l} - (\kappa^2)^2\Delta_L & -\kappa^2\Delta_L^2 & -2\kappa^2\Delta_L\phi_l^2 & (R_X\phi_1)_T - k^2(\Lambda_1\phi_1)_T & (R_X\phi_1)_T - k^2(\Lambda_2\phi_1)_T \\
(R_X\phi_2)_T & k^2\Delta_L^2 & R^*_{X_l} - (\kappa^2)^2\Delta_L & -2\kappa^2\Delta_L\phi_l^2 & k^2(\Lambda_1\phi_1)_T + (R_X\phi_2)_T & k^2(\Lambda_2\phi_1)_T + (R_X\phi_2)_T \\
0_{L} & 0_{L} & 0_{L} & 0 & \Delta T & 0 \\
0_{L} & 2\phi_l^T & 0_{L} & 0 & 0 & 0 \\
\Delta X^T & 0_l & 0_l & \Delta \omega & \Delta \phi & \Delta \alpha \\
\end{bmatrix}
$$

where the derivatives $(\Lambda_1)_x$ and $(\Lambda_2)_x$ are not null only if the system parameter $\alpha$ is involved in matrix $M$ or $C$.

6. Applications

The proposed bifurcation tracking technique is applied to a nonlinear energy sink (NES) and a nonlinear Jeffcott rotor in order to demonstrate its capabilities and performance. These applications also aim at showing that bifurcation tracking can be used as an efficient tool for the design and performance tuning of nonlinear dynamical systems.

6.1. Nonlinear energy sink (NES)

The first application concerns a linear oscillator with an attached nonlinear energy sink (NES) under harmonic external forcing. Unlike common linear vibration absorbers, NES are efficient in a wide range of frequencies and over a range of amplitudes of the external forcing [54]. This is due mainly to a qualitatively different dynamical behaviour in close vicinity of the main resonance, where the NES can exhibit quasi-periodic rather than periodic response [55, 56]. Indeed, the energy of vibration is transferred to the NES and damped out in quasi-periodic regime, leading to energy level reduction and attenuation of vibrations of the primary oscillator.

In the case of strongly nonlinear vibration absorber, it was shown in [57] that, depending on system parameters, weak or strong quasi-periodic regimes occur, both of them providing efficient vibration absorption. Thus, in order to perform a careful tuning, it is essential to determine the range of parameters in which quasi-periodic beating responses are possible. Since a weak quasi-periodic response relates to a periodic response loosing its stability via NS bifurcation, the boundaries for the quasi-periodic response can be obtained by the parametric continuation of NS bifurcations introduced in this paper.

The system under consideration consists of a linear oscillator and a small essentially nonlinear attachment, as described in [57]. The linear oscillator is the primary structure with mass $m_1$ and the nonlinear attachment with small mass $m_2$ is the NES. They are coupled through a pure cubic elastic force and a viscous damper. For simplicity, the stiffness of the linear oscillator is chosen such that its resonance frequency is equal to 1. The system is governed by the following equations

$$
\ddot{x}_1 + \epsilon \lambda (\dot{x}_1 - \dot{x}_2) + x_1 + \epsilon k_{nl}(x_1 - x_2)^3 = \epsilon A \cos(\omega t) \\
\epsilon \ddot{x}_2 + \epsilon \lambda (\dot{x}_2 - \dot{x}_1) + \epsilon k_{nl}(x_2 - x_1)^3 = 0
$$

with $x_1$ and $x_2$ the displacements of the linear oscillator and the absorber (NES), respectively, $\epsilon = m_2/m_1 \ll 1$ the mass ratio, $\epsilon \lambda$ the damping coefficient, $\epsilon k_{nl}$ the nonlinear stiffness coefficient and $\epsilon A$ the amplitude of the external force. In the following, $\epsilon = 0.1$ and $\lambda = 0.4$ are fixed while $k_{nl}$ and $A$ are varied for tuning purpose.

First, $A = 0.3$ is kept fixed and the dynamics of the coupled nonlinear system is investigated for several values of $k_{nl}$. The forced response is computed by HBM and continuation technique as described in Section 2. Convergence of the results is obtained with $H = 3$ harmonics and verified by comparison with time integration. Stability analysis and detection of bifurcations are performed according to Sections 3 and 4. The amplitude $x_1$ of the linear oscillator...
is plotted in Figure 3, where solid lines stand for stable periodic solutions, dashed lines for unstable ones and triangle markers for NS bifurcations. For $k_{nl}=1$, a periodic response is obtained for all frequencies. For greater values of $k_{nl}$, the NS bifurcations clearly define frequency zones in which the quasi-periodic beating response is the only stable response. The system response in these quasi-periodic zones can be easily computed by time integration. Since its amplitude is modulated, the total average system energy

$$E_{tot} = \left[ \frac{x_1^2}{2} + \epsilon \frac{x_2^2}{2} + \frac{x_2^4}{4} + \epsilon k_{nl} \frac{(x_1 - x_2)^4}{4} \right]$$

is used instead, with the average performed over a period of time 50 times longer than the modulation period. The total system energy $E_{tot}$ vs. excitation frequency $\omega$ is plotted in Fig. 4. In this figure, the unstable periodic responses have been replaced by stable quasi-periodic ones in the zones of quasi-periodic beating. It can be observed that the level of total system energy is reduced when $k_{nl}$ is increased, therefore demonstrating the absorber efficiency.

Obtaining the boundaries for the quasi-periodic beating response by this way is a tedious task, since the computation of frequency response and the detection of bifurcations have to be repeated for each value of $k_{nl}$ in the range of interest. An efficient alternative consists in using the direct bifurcation tracking presented in Section 5. To do so, a response curve is first computed for an arbitrary fixed value of $k_{nl}$, e.g. $k_{nl}=3$, until the first NS bifurcation is detected. Then, $k_{nl}$ is considered as a new unknown and this NS bifurcation is used as a starting point for the direct continuation of the curve of NS bifurcations. Doing so, the boundaries for the quasi-periodic beating response are obtained with only one computation. This curve is represented as a 3D-plot in Fig. 5. The frequency responses plotted in Fig. 5 for some values of $k_{nl}$ were not used for the computations. They are presented here to make the interpretation of the 3D-plot easier and to show that the direct NS tracking works as expected and is accurate.

Projections of the NS tracking curve on the $E_{tot} - k_{nl}$ and $k_{nl} - \omega$ planes are plotted in Fig. 6. They provide useful information for designing the NES. The areas inside and outside the NS tracking curve correspond to quasi-periodic beating responses and to periodic responses without beating, respectively. It can be seen from Fig. 6(a) that the total system energy for beating responses decreases monotonically with $k_{nl}$ increasing. Moreover, for a given value of $k_{nl}$, the system energy level is comprised between the two values given by the NS tracking curve. From Fig. 6(b), the range of frequencies in which a beating response occurs can be directly read for each value of $k_{nl}$. It can also be observed that in zone (A) for $k_{nl} < 1.92$ there is no possibility of a quasi-periodic beating response. In zone (B) for $1.92 < k_{nl} < 7.78$, there is a wide range of frequencies centered on the resonance. This operating zone is optimal and the highest value of $k_{nl}$ in this zone ($k_{nl} \approx 7.78$) appears to be the optimal one. In zone (C) for $7.78 < k_{nl} < 11.28$, the quasi-periodic area is divided into two smaller areas separated by a periodic area. The left-hand side quasi-periodic area is really narrow and the right-hand side one is not centered on the resonance. As a consequence, this is not an optimal operating zone. In zone (D) for $k_{nl} > 11.28$, the quasi-periodic area is not centered on the resonance. In

![Figure 3: Vibration amplitudes of the main mass $x_1$ vs. excitation frequency for $\epsilon=0.1, \lambda=0.4, \Lambda=0.3$ and various nonlinear stiffness coefficients $k_{nl}=1, 3, 5, 7, 9$. Stable and unstable periodic responses.](image)
Figure 4: Average total system energy for $\epsilon=0.1$, $\lambda=0.4$, $A=0.3$ and $k_{nl}=1, 3, 5, 7, 9$. Stable periodic and quasiperiodic solutions.

Figure 5: Frequency responses and Neimark-Sacker bifurcation tracking for $\epsilon=0.1$, $\lambda=0.4$, $A=0.3$ and varying $k_{nl}$.

Figure 6: Projections of the Neimark-Sacker bifurcation tracking for $\epsilon=0.1$, $\lambda=0.4$, $A=0.3$ and varying $k_{nl}$.
Figure 7: Average total system energy for $\epsilon=0.1$, $\lambda=0.4$, $k_{nl}=5$ and $A=0.1, 0.2, 0.3, 0.4$. Stable periodic and quasi-periodic solutions.

Figure 8: Frequency responses and Neimark-Sacker bifurcation tracking for $\epsilon=0.1$, $\lambda=0.4$, $k_{nl}=5$ and varying $A$.

Figure 9: Projection of the Neimark-Sacker bifurcations tracking for $\epsilon=0.1$, $\lambda=0.4$, $k_{nl}=5$ and varying $A$. 
addition, the frequency responses for these values of $k_{nl}$ are very complex and there may be other stable solutions than the expected quasi-periodic response. Thus, this is not a safe operating zone.

The amplitude $A$ of the external force is now used as the varying parameter while other system parameters $\epsilon=0.1$, $\delta=0.4$ and $k_{nl}=5$ are kept fixed. The total system energy vs. excitation frequency $\omega$ is plotted in Fig. 7 for $A=0.1$, 0.2, 0.3, 0.4. As expected, it can be observed that, away from the resonance where the response is periodic, the level of total system energy increases with $A$. However, in the vicinity of the resonance where quasi-periodic beating response occurs, the average energy level is almost the same whatever the value of $A$, therefore demonstrating the constant absorber efficiency over a range of amplitudes of the external forcing. In order to determine the boundaries of the quasi-periodic beating area, NS tracking is performed, starting from the first detected NS bifurcation on the frequency curve for $A=0.3$. The resulting tracking curve in presented in the 3D-plot of Fig. 8 and its projections on the $E_{tot} - A$ and $A - \omega$ planes are plotted in Fig. 9. Again, four operating zones can be identified.

In zone (A) for $A < 0.186$ there is no possibility of a quasi-periodic beating response. Zone (B), for $0.186 < A < 0.374$, defines an optimal operating zone since it contains a wide range of frequencies centred on the resonance. In zone (C) for $0.374 < A < 0.45$, the main quasi-periodic area is not centred any more on the resonance. As a consequence, this is not an optimal operating zone. Zone (D), for $A > 0.45$, is not a safe operating zone because the quasi-periodic area is not centred on the resonance and there may be other stable solutions than the expected quasi-periodic response.

From the computations presented in this example, it appears that the direct parametric continuation of bifurcation points exhibits a considerable efficiency and can be used as a fast tuning tool for the design of NES systems, since the optimal range of operating parameters can be determined with only one computation.

### 6.2. Nonlinear Jeffcott rotor

The second test case is the modified Jeffcott rotor presented in Fig. 10 which can interact at the disk location with a stator modelled as an additional stiffness [12, 58]. The rotor is made of a weightless shaft carrying a disk with mass $m$ and radius $R_{disc}$ at the middle of the span. The clearance between the rotor and the stator is denoted by $h$. The mass center of the rotor is located at a distance $e$ from its geometrical center. The stator, which is rigidly fixed, has an elastic contact surface modelled as a symmetrical set of radial springs with isotropic stiffness $k_c$.

![Nonlinear Jeffcott rotor with stator contact](image)

Let the investigated motion be located in the first natural frequency range. Therefore there is no gyroscopic effect to take into account in the equations of motion at the disk location described by

\[
mx + cx + kx + k_c(1 - \frac{h}{r})(x - \mu y \text{ sign}(v_{rel})) = me_0^2 \cos \omega t
\]

\[
m\dot{y} + cy + ky + k_c(1 - \frac{h}{r})(\mu x \text{ sign}(v_{rel}) + y) = me_0^2 \sin \omega t
\]

with $k$ the stiffness of the shaft, $r = \sqrt{x^2 + y^2}$ the radial displacement, $me_0^2$ the mass unbalance amplitude and $v_{rel} = (\dot{z}, y - \dot{x}) + R_{disc} \omega$ the relative velocity between the rotor and the stator at the contact point. When $r < 0$, there is no rotor-stator contact and $k_c$ is set as nil.

All the calculations are carried out with the same set of parameters as in [12] and [58]: $m = 1$ kg, $c = 5$ N.s/m, $k = 100$ N/m, $k_c = 2500$ N/m, $h = 0.105$ m, $e = 0.1$ m, $R_{disc} = 20h$, $\omega_0 = \sqrt{k_c/m} = 50$ rad/s, except that the friction coefficient $\mu$ is considered as the variable parameter.

15
Firstly, the calculation of the system response to the unbalance force is performed for a friction coefficient $\mu = 0.2$ by HBM and continuation technique. Based on comparison with results obtained by time integration, $N = 15$ harmonics are used for HBM computations. This high number of harmonics is required for a good representation of the transition between the no-contact and the contact solution. Continuation, stability analysis and detection of bifurcations, as described in Sections 3 and 4, are performed at the same time. The maximum amplitude of the dimensionless radial displacement of the disk $r/h$ with respect to the dimensionless excitation frequency $\tilde{\omega} = \omega/\omega_0$ is plotted in Fig. 11, where solid lines stand for stable periodic solutions, dashed lines for unstable ones, dotted lines for quasi-periodic stable solutions, circle markers for LP and triangle markers for NS bifurcations. Periodic and quasi-periodic solutions are calculated by HBM and time integration respectively. There is no contact between the rotor and the stator until $r/h = 1$ ($\tilde{\omega} \approx 0.154$). Then, the amplitude exceeds the initial clearance and the rotor rubs permanently against the stator in a so-called synchronous full annular rub motion. This periodic rub motion remains stable until $\tilde{\omega} = 0.289$ where a NS bifurcation is detected. For higher values of $\tilde{\omega}$, the periodic rub motion is unstable and the only stable solution is the quasi-periodic partial rub motion characterized by rebounds and intermittent contact between the rotor and the stator. This quasi-periodic partial rub motion remains stable until $\tilde{\omega} \approx 0.46$. At this stage, there is a sudden jump in amplitude and a backward whirl motion is triggered, which may severely damage the rotor system in a very short time. The behaviours for $\mu = 0.05$ and $\mu = 0.11$ (Fig. 12) are qualitatively different. For $\mu = 0.05$, the periodic synchronous full annular rub motion is stable until the end of the contact indicated by the limit point at $\tilde{\omega} \approx 1$ and is the only possible solution during the rotor-stator contact. For $\mu = 0.11$, the response is also periodic after the contact initiation but it does not remain stable until the limit point is reached. Indeed, two NS bifurcations are found
Figure 13: Limit points tracking and Neimark-Sacker bifurcations tracking of the Jeffcott rotor as a function of friction coefficient $\mu$.

Figure 14: Projection of the bifurcation tracking on $\bar{\omega} - \mu$ plane. Comparison with results of Figs. 11 and 12.

Figure 15: Projection of the bifurcation tracking on $\bar{\omega} - \mu$ plane. Identification of the regions with different dynamical regimes.
at $\dot{\omega} = 0.847$ and $\dot{\omega} = 0.963$. Between these two frequencies, the only stable motions are the quasi-periodic partial rub and the no-contact motions.

From this phenomenological analysis, it appears that the nature of the motion is highly dependent on the friction coefficient $\mu$ and on the excitation frequency $\dot{\omega}$. Thus, a parametric analysis defining the boundaries of the different dynamical regimes with respect to these two parameters is of great interest for designers and operators. Again, this parametric analysis can be performed by means of the direct bifurcation tracking presented in Section 5. To do so, a response curve is first computed for $\mu=0.2$, until a NS bifurcation or a LP is detected. Then, $\mu$ is considered as a new unknown and this NS bifurcation or LP is used as a starting point and the bifurcation tracking is performed in both directions (increasing and decreasing values of $\mu$). Doing so, the boundaries for the no-rub and the quasi-periodic motions are obtained with only one computation. These LP and NS tracking curves are represented as a 3D-plot in Fig. 13. A few response curves are also plotted to make the interpretation of the 3D-plot easier.

The projections of the tracking curves on plane $\dot{\omega} - \mu$ plane are plotted in Figs. 14 and 15. For a given value of $\mu$, these curves provide the frequencies corresponding to the occurrence of LP and NS bifurcations. The horizontal lines in Fig. 14 for $\mu = 0.05, 0.11$ and $0.2$ permit to compare the results of the bifurcation tracking with the response curves of Figs. 11 and 12. Their intersections with the vertical lines and the two tracking curves precisely delimit the different dynamical regimes encountered along the response curves. Thus, the two LP and NS tracking curves divide the $\dot{\omega} - \mu$ plane into several regions corresponding to the different possible dynamical regimes of the rotor. These regions are identified in Fig. 15. The ends of the NS tracking curve give the two frequencies $\dot{\omega} = 0.154$ and $\dot{\omega} = 0.854$ corresponding to the initiation and end of the contact. The NS tracking curve also corresponds to the boundary of the quasi-periodic regime. The motion is periodic (synchronous full annular rub motion) below this curve and quasi-periodic (partial rub motion with rebounds) above it. Consequently, for $\mu < 0.108$, the motion is purely periodic and the rotor undergoes only full annular rub during the contact with the stator. For $0.108 < \mu < 0.36$, the motion during contact can be periodic or quasi-periodic, depending on $\dot{\omega}$, and the range of periodic motion decreases with $\mu$ increasing. For $\mu > 0.36$, the motion during contact is purely quasi-periodic. Finally, it can observed that the obtained NS tracking curve is in good agreement with the analytical results from Jiang [58].

The computational cost for each numerical procedure is summarised in Table 1. The computation of a single response curve requires roughly 50-60 continuation steps. For $\mu=0.2$, 56 adaptive continuation steps with an average number of 3 Newton-Raphson iterations per step are necessary to compute the whole response curve with an accuracy $\varepsilon = 10^{-6}$ and assess stability by Hill’s method. The computational time for one step of response curve continuation is normalized to 1 and used as a reference time. It can be inferred from this table that one step of LP and NS tracking is respectively 1.6 and 2.3 times more costly than one step of response curve continuation. This increase is related to the larger size of the augmented systems to be solved. For this example, the LP and NS tracking require 54 and 79 continuation steps respectively. Therefore, the computational costs for the complete LP and NS trackings appear to be about 1.5 and 3 times higher than for a complete response curve. However, these costs do not include the computation of the starting bifurcation point, which requires the continuation of the response curve for $\mu=0.2$ until the detection of the bifurcation points. For this application, 40 steps and 17 steps of continuation (with cost 1) are necessary to reach and detect the LP and NS bifurcation respectively. Thus, the actual costs of the complete LP and NS trackings are 87+40=127 and 182+17=199 respectively, i.e. they are equivalent to the computation of 2.3 and 3.5 complete response curves.

7. CONCLUSIONS

An efficient frequency-domain method for the fast parametric analysis of bifurcations of nonlinear dynamical systems has been presented. Instead of computing several response curves and detecting the bifurcation points, the

<table>
<thead>
<tr>
<th>Type of computation</th>
<th>Number of steps</th>
<th>Relative average time per step</th>
<th>Total time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Response curve + stability ($\mu=0.2$)</td>
<td>56</td>
<td>1</td>
<td>56</td>
</tr>
<tr>
<td>LP tracking</td>
<td>54</td>
<td>1.6</td>
<td>87</td>
</tr>
<tr>
<td>NS tracking</td>
<td>79</td>
<td>2.3</td>
<td>182</td>
</tr>
</tbody>
</table>

Table 1: Computational cost of the bifurcation tracking for the Jeffcott rotor
proposed method consists in directly tracking the bifurcation points when a system parameter such as the excitation or nonlinearity level is varied. To this end, a so-called extended system comprising the equation of motion and an additional equation characterizing the bifurcation of interest is solved by means of the Harmonic Balance Method coupled with an arc-length continuation technique. In particular, an original extended system for the detection and tracking of Neimark-Sacker (secondary Hopf) bifurcations has been proposed. Even if the additional equations characterizing the bifurcations increase the size of the problem, it is shown that the computational cost can be reduced with the use of a block elimination algorithm. Moreover, the additional equations have the same form and involve the same derivatives whatever the type of bifurcation, thus making the numerical implementation easier.

The examples considered in this paper have shown the interest of the proposed bifurcation tracking for the parametric analysis of a nonlinear vibration absorber (NES) and a nonlinear rotor system. Indeed, with only one computation a map showing the stability boundaries and changes of dynamical regime has been obtained. Moreover, the bifurcation tracking has been shown to be only 2 or 3 times more costly than a conventional response curve calculation. As a result, it can be used by engineers at the design stage to tune nonlinear systems efficiently.

The numerical developments have been fulfilled in both Matlab and Cast3M [59] softwares, paving the way for applications of the method to the nonlinear dynamics of structures modelled with finite elements.

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References


