Electrostatic (capacitive) vibration energy harvesters (E-VEHs) convert kinetic energy of the environment into electrical energy using a capacitive transducer [1]. E-VEHs are particularly suitable for microscale implementation, and in recent years they have become the subject of a growing area of research [2]–[4]. The main issue of e-VEH design is the optimization of converted power for given environmental conditions and given limitations on the electrical and mechanical components. One of the limits of convertible power is set by the complexity and nonlinearity of the system, as demonstrated in [5]. In particular, desired harmonic oscillations are possible only for some set of system parameters. Otherwise, the system displays chaotic behaviour (non-harmonic modes) in which the conditioning electronics cannot operate properly. For these reasons, optimal design of an e-VEH requires a deep understanding of the overall system dynamics, including nonlinear effects.

The work [6] introduced an analytical tool for analysis of a e-VEH as the coupled system, while ref. [7] studies steady-state oscillations in the harvester applying a formal analytical approach. Building on these works, the aim of this paper is to extend the analysis of the e-VEH behaviour in order to identify the limit of regular harmonic operation of an e-VEH as the coupled system, while ref. [7] studies steady-state oscillations, period doubling bifurcation and transition to chaos. This allows us to bound regions of control parameters where the system displays desired regular oscillations and, therefore, to identify maximal harvestable power for a particular architecture.

I. INTRODUCTION

Electrostatic (capacitive) vibration energy harvesters (E-VEHs) convert kinetic energy of the environment into electrical energy using a capacitive transducer [1]. E-VEHs are particularly suitable for microscale implementation, and in recent years they have become the subject of a growing area of research [2]–[4]. The main issue of e-VEH design is the optimization of converted power for given environmental conditions and given limitations on the electrical and mechanical components. One of the limits of convertible power is set by the complexity and nonlinearity of the system, as demonstrated in [5]. In particular, desired harmonic oscillations are possible only for some set of system parameters. Otherwise, the system displays chaotic behaviour (non-harmonic modes) in which the conditioning electronics cannot operate properly. For these reasons, optimal design of a e-VEH requires a deep understanding of the overall system dynamics, including nonlinear effects.

The work [6] introduced an analytical tool for analysis of a e-VEH as the coupled system, while ref. [7] studies steady-state oscillations in the harvester applying a formal analytical approach. Building on these works, the aim of this paper is to extend the analysis of the e-VEH behaviour in order to identify the limit of regular harmonic operation of an e-VEH that employs a gap-closing transducer (one of the most widely used). We study bifurcations of the steady-state orbit and determine the condition for the period doubling bifurcation.

II. STATEMENT OF THE PROBLEM

A simple electrostatic harvester consists of a high-Q resonator, a variable capacitor (transducer) C_{trans}, and a conditioning circuit (Fig. 1). The displacement x of the mass-spring-damper system driven by the external oscillations and affected by the transducer force is described by

\[ \ddot{x} + \frac{b}{m} \dot{x} + \omega_0^2 x = A_{ext} \cos(\omega_{ext}t + \vartheta_0) + f_t(x, \dot{x}) / m \]  

where m is the mass of the resonator, b is the damping factor, \( \omega_0 = \sqrt{k/m} \) is the natural frequency, k is the spring constant, \( A_{ext} \) is the external acceleration amplitude, \( \omega_{ext} \) is the external frequency and \( \vartheta_0 \) is the phase of the external force. \( f_t(x, \dot{x}) \) is the force generated by the transducer. The detailed description of the conditioning circuit can be found in [4], [6].

Depending on the architecture of the conditioning circuit, at each cycle one quantity can be fixed on the transducer when \( C_{trans} = C_{max} \): the charge \( Q_0 \), the energy \( W_0 \), or the voltage \( V_0 \). In this paper, we consider the most common case described in [4] where the energy \( W_0 \) is fixed. For a gap-closing transducer, the capacitance function is [5], [6] \( C_{trans} = C_0 / (1 - x/d) \), and the transducer force is

\[ f_t(x, \dot{x}) = \begin{cases} \frac{W_0}{d(1-x_{max}/d)}, & \dot{x} \leq 0 \\ 0, & \dot{x} > 0 \end{cases} \]

where \( d \) is the equilibrium gap and \( x_{max} \) is the maximal displacement.

In order to reduce the number of parameters and outline only essential ones, the following normalised variables are introduced: time \( \tau = \omega_0 t \), dissipation \( \beta = b/(2m\omega_0) \), normalised external frequency \( \Omega = \omega_{ext}/\omega_0 = 1 + \sigma, y = x/d, \) \( \alpha = A_{ext} / (d\omega_0^2) \) and \( \nu_0 = W_0 / (d^2m\omega_0^2) \). Equation (1) is now written as

\[ y'' + 2\beta y' + y = f_t(y, y') + \alpha \cos(\Omega \tau + \theta_0) \]

where the prime denotes the derivative with respect to dimensionless time \( \tau \) and the function \( f_t(y, y') \) is the normalised version of (2):

\[ f_t(y, y') = \begin{cases} \frac{\nu_0}{(1-y_{max})}, & y' \leq 0 \\ 0, & y' > 0 \end{cases} \]

While the mass, the natural frequency and other parameters are fixed, the acceleration \( A_{ext} \) and the energy \( W_0 \) (and their
dimensionless analogues $\alpha$ and $\psi_0$) may vary and affect the behaviour of the system. We will refer to them as the control parameters of the dynamical system. Typical parameters used in the numerical simulations of later sections are listed in Table I.

<p>| Table I |</p>
<table>
<thead>
<tr>
<th>Parameters of the system</th>
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<td>$m$</td>
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<td>$A_{ext}$</td>
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III. STEADY-STATE OSCILLATIONS

In this section we very briefly discuss steady-state behaviour. Substantial results that we have recently obtained for the system with two configurations of the transducer, area overlap [8] and hyperbolic [5], are reported in [7]. We analyse the steady-state behaviour by employing the multiple scales method (MSM) [9], a type of perturbation technique that is often applied for the analysis of weakly nonlinear oscillators of various types, both autonomous and under external excitation. The solution obtained from the MSM has the form

$$y_0(\tau) = y_{av.0} + a_0 \cos((1 + \sigma)\tau + \theta_0 - \psi_0)$$  (5)

where $a_0$, $y_{av.0}$ and $\psi_0$ are the steady-state amplitude, average displacement (constant shift) and phase of oscillations (the index '0' emphasizes that this is a steady-state solution). The amplitude $a_0$ and the phase $\psi_0$ are found from the equations:

$$\frac{\alpha}{2} \sin \psi_0 = \beta a_0 + \frac{b_1(y_{m.0})}{2}$$

$$\frac{\alpha^2}{4} = \left( \beta a_0 + \frac{b_1(y_{m.0})}{2} \right)^2 + \left( a_0 + \frac{b_1(y_{m.0})}{2} \right)^2$$  (6)

where $y_{m.0}$ denotes the maximal displacement $y_{m.0} = y_{av.0} + a_0$. The transducer force is a periodic function since the solution (5) is a harmonic oscillation. Therefore, we have used the Fourier series for $f_t$

$$f_t(\tau) = f_0 + a_1 \cos \theta(\tau) + b_1 \sin \theta(\tau)$$

where $\theta(\tau) = (1 + \sigma)\tau + \theta_0 - \psi_0$ and $f_0$, $a_1$ and $b_1$ are the standard coefficients of the Fourier series but dependent on the amplitude $a_0$ and the average displacement $y_{av.0}$. Note that due to the zero harmonic in the Fourier series, the oscillation (5) has this constant shift $y_{av.0} = f_0$.

The orbit given by (5)-(6) is stable if the following conditions are fulfilled:

$$2\beta + \frac{b_1}{2a_0} > 0$$

$$\left( \beta + \frac{b_1}{2a_0} \right) \left( \beta + \frac{b_1}{2a_0} \right) + \left( \sigma + \frac{a_1}{2} \right) \left( \sigma + \frac{a_1}{2} \right) > 0$$  (7)

If the above conditions are not fulfilled, the orbit that is defined by these $a_0$, $y_{av.0}$ and $\psi_0$ is unstable, or a saddle orbit. The above stability condition is necessary, but not sufficient.

For the gap closing transducer, the coefficients are

$$f_0 = \frac{\nu_0}{2(1 - y_m)}$$

$$a_1 = 0$$

$$b_1 = \frac{2\nu_0}{\pi(1 - y_m)}$$  (8)

IV. NONLINEAR BEHAVIOUR AND BIFURCATIONS

A. Motivation for Further Analysis

In the previous section we noted the necessary condition for stability following ref. [7]. However, it is known that for nonlinear oscillators increase in the amplitude of the external force or other parameters typically leads to bifurcations of previously stable orbits and, eventually, to irregular, chaotic behaviour [10]. We have carried out a series of numerical simulations of the system shown in Fig. 1 using a VHDL-AMS model [11]. A typical result is shown in Fig. 2. A slowly growing ramp of the acceleration envelope $A_{ext}$ versus time is depicted in Fig. 2a. At the same time, we trace the displacement of the resonator versus time in Fig. 2b. Since the ramp changes very slowly, we consider this process as quasi-static and therefore we observe the evolution of the steady-state behaviour of the e-VEH at a variation of $A_{ext}$. This plot can be seen as an analogue of a bifurcation diagram.

According to Fig. 2, there are the following qualitative changes (bifurcations) in the system behaviour with a change of the parameter $A_{ext}$: (i) appearance of steady-state harmonic oscillations (fragment 1 in the figure); (ii) period doubling bifurcation (fragment 2, see Fig. 3a) and (iii) transition to chaos (fragment 3, see Fig. 3b). Two closed orbits and a portion of a chaotic trajectory at fixed $A_{ext}$ and $W_0$ that illustrates the above bifurcations are shown in Fig. 4.
and shows the doubling bifurcation. Figure (b) is a magnified fragment 3 and in (6):

This means that in order to put the system in oscillations at harmonic steady-state oscillations (5) at $t_0 = 0$, the envelope of the external attractor at $t_0 = 0$. We obtain the equation

$$\frac{d^2y}{dt^2} + 2\beta \frac{dy}{dt} + \zeta = f_0(y_{m,0})y_{m,\zeta} + b_1(y_{m,0})y_{m,\zeta} \sin(\Omega \tau + \theta_0 - \psi_0)$$

(11)

that generally describes the evolution of small deviations from the steady-state orbit. Note that the prime for the functions $f_0$ and $b_1$ is taken with respect to their argument, i.e. $y_m$. This equation contains the variable $y_{m,\zeta}$ which is undefined analytically in the most general case. To address this issue, we can choose to launch the initial deviation at the moment when $y' = 0$, i.e. then, $y_{m,\zeta}(0) = \zeta(0)$, and we will use $\zeta$ instead of $y_{m,\zeta}$. This ‘trick’ significantly simplifies the analysis.

$$\frac{d^2\zeta}{dt^2} + 2\beta \frac{d\zeta}{dt} + \zeta(1 - f_0(y_{m,0}) - b_1(y_{m,0}) \sin(\Omega \tau + \theta_0 - \psi_0)) = 0$$

(12)

The latter can be reduced to a well-known parametric equation, the Mathieu Equation

$$\frac{d^2\zeta}{dt^2} + (\delta + 2\varepsilon \cos 2t)\zeta = 0$$

(13)

by introducing the variable transformations:

$$\zeta = \exp(-\beta t)\xi, \quad \tau = 2t/\Omega + \tau_0, \quad \tau_0 = (\psi_0 - \theta_0 - \pi/2)/\Omega$$

$$\delta = \frac{4}{\Omega^2}(1 - \beta^2 - f_0(y_{m,0})), \quad 2\varepsilon = \frac{4}{\Omega^2}b_1(y_{m,0})$$

For equation (13), it is known that for certain $\delta$ and $\varepsilon$, there exist areas of so-called ‘parametric instability’ when the solution of (13) $\xi = 0$ is unstable [9]. Returning to the original system, this means that the small deviations $\zeta$ of the steady-state $y_0$ will start increasing instead of decaying. The areas of parametric instability for the Mathieu equation are found in the latter reference. Thus, we can determine stability of the orbit simply by checking whether $\delta$ and $\varepsilon$ defined for equation (12) lie in one of parametric instability areas.

However, a more complete analysis of parametric equations can be obtained by employing Floquet theory [10] that not only provides us with bifurcation values of parameters but also indicates what type of bifurcation is undergone by the original orbit. For this purpose, one constructs a matrix equation based on the equation for small perturbations (12):

$$\begin{pmatrix} \zeta_{1}' \\ \eta_{1}' \\ \zeta_{2}' \\ \eta_{2}' \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \\ -2\beta & 0 \end{pmatrix} \begin{pmatrix} \zeta_{1} \\ \eta_{1} \\ \zeta_{2} \\ \eta_{2} \end{pmatrix}$$

(14)

where the prime denotes the derivative with respect to time $\tau$, $\eta = d\zeta/d\tau$ and the time dependent coefficient $K(\tau)$ is $K(\tau) = [-1 + f_0'(y_{m,0}) + b_1'(y_{m,0}) \sin(\Omega \tau + \theta_0 - \psi_0)]$. The latter allows one to find a set of fundamental solutions (two fundamental solutions in our particular case). Denoting $Z = (\xi_1, \eta_1, \xi_2, \eta_2)$, we assume initial conditions for the set (14) in the form of the identity matrix $Z(0) = I$. Solving (14) on one period $T = 2\pi/\Omega$ we obtain $M = Z(T)$, the monodromy matrix. The eigenvalues of the monodromy matrix $M$, the Floquet multipliers $\mu_k$, indicate stability of the orbit. The orbit is asymptotically stable if there are no eigenvalues outside the unit circle. If at a variation of control parameter a Floquet multiplier leaves the unit circle through $-1$, the original fixed point or orbits undergoes a doubling bifurcation; if through +1, a transcritical, symmetry-breaking or cyclic-fold bifurcation, and, finally, if two complex conjugate multipliers
Consider that the regime becomes chaotic.

Lyapunov exponent is given by the expression:

\[ \lambda = \frac{1}{t} \lim_{t \to \infty} \log \left( \frac{\|x(t) - x(0)\|}{\|x(0) - x(0)\|} \right) \]

This formula can be implemented in numerical simulations of the original nonlinear system (3) by solving two sets of equations (14) which yielded the monodromy matrix of the system. We trace when and how one of the Floquet multipliers leaves the unit circle. We have found out that the multipliers cross it through \( \lambda_1 \) (therefore, it is a doubling bifurcation) and determined the bifurcation values of the parameters. This agrees with the modelling shown in Fig. 3a that clearly illustrate the period doubling of the original orbit. Note that resulting oscillations are stable as well.

Finally, line 3 indicates when the largest Lyapunov exponent becomes positive and the system displays chaotic oscillations. This line agrees with the modelling shown in Fig. 3b. It is very interesting that the system displays only one doubling bifurcation and therefore the transition to chaos is not through the Feigenbaum scenario but rather through intermittency.

**V. Conclusions**

This study analysed an e-VEH as a nonlinear oscillator, focusing in particular on the limits of regular behaviour. The analysis presented here quantifies the phenomena observed previously in the Behavioural model [5] and provides necessary and sufficient conditions for a regular harmonic mode of the e-VEH. This provides designers of e-VEHs with a powerful tool allowing them to understand fundamental limits of the system at early stages of design. All analytical discoveries are verified by simulations of the behavioral model carried out with VHDL-AMS.

**References**