Selective monostability in multi-stable systems

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We propose a robust method that allows a periodic or a chaotic multi-stable system to be transformed to a monostable system at an orbit with dominant frequency of any of the coexisting attractors. Our approach implies the selection of a particular attractor by periodic external modulation with frequency close to the dominant frequency in the power spectrum of a desired orbit and simultaneous annihilation of all other coexisting states by positive feedback, both applied to one of the system parameters. The method does not require any preliminary knowledge of the system dynamics and the phase space structure. The efficiency of the method is demonstrated in both a non-autonomous multi-stable laser with coexisting periodic orbits and an autonomous Rössler-like oscillator with coexisting chaotic attractors. The experiments with an erbium-doped fibre laser provide evidence for the robustness of the proposed method in making the system monostable at an orbit with dominant frequency of any preselected attractor.

1. Introduction

Multi-stability is a universal, essentially nonlinear phenomenon that has been found in almost all areas of science and nature—from lasers [1,2] and chemical reactions [3] to climate [4,5] and brain [6,7]. Multi-stability also contributes to the fundamental dynamics of neurons and neuronal networks [8–10] involving cell differentiation and hysteresis and is compulsory for implementing associative memories, signal processing,
pattern recognition and optimization problems [11–13]. The coexistence of attractors often appears in systems with time-delayed feedback [14,15] and in systems with small dissipation [4].

In a real system with multiple coexisting attractors, it is very difficult to keep the trajectory in a particular attractor due to extremely high sensitivity of the multi-stable system to external perturbations or noise. Several feedback and non-feedback control strategies have been developed to direct the system trajectory to a desired attractor (see [4] and references therein). Feedback control [16–19] and forecast-based control [20] methods allow attractor selection without changing the structure of basins of attraction. Instead, non-feedback control, e.g. in the form of external modulation [21–23], destroys some of attractors resulting in monostability, but it does not allow in every case the selection of a particular attractor. In practice, the possibility of converting a multi-stable system to a monostable one is very much in demand because this would allow one to avoid any unpredictable switch to another coexisting state that may be caused by environmental fluctuations or increasing internal noise. Modern engineering and laser technologies require not only a stable output, robust to noise and sudden surges in parameters or variables [24–27], but also the possibility to choose a state with specific properties. Multi-stability has to be avoided not only in engineering but also in medicine, where serious diseases such as epilepsy [7,28] and cardiac arrhythmia [29,30] are thought to be caused by the coexistence of normal and pathological states.

Although the transformation from a multi-stable to a monostable regime can often be achieved by just changing parameter values, in many situations a large variation of system parameters is undesirable and is not always even possible. As we already mentioned above, due to several limitations, the existing methods for controlling multi-stability are not able to make a system monostable at an attractor with characteristic properties of any one of coexisting states; for example, the method of attractor annihilation by periodic modulation [21] can destabilize only those attractors whose eigenfrequencies are close to the modulation frequency [31]. In this paper, we address the question: Is it possible to design a method capable of eliminating all coexisting orbits except the one with desired properties, i.e. to make the system monostable at an orbit with dominant frequency of any one of the coexisting attractors? Our results give a positive answer to this question. In the following, we will show how to design such a method, apply it to both non-autonomous and autonomous systems and test it experimentally in a multi-stable fibre laser with four coexisting periodic orbits.

Let us consider a general nonlinear dynamical system

\[ \dot{x}(t) = f(x(t), p), \quad x \in \mathbb{R}^n, \tag{1.1} \]

where \( x = (x_1, \ldots, x_j, \ldots, x_n) \) is the state vector and \( p \) is a parameter. We suppose that the system (1.1) exhibits the coexistence of \( q \) periodic or chaotic attractors \( A = A_1, \ldots, A_q \subset \mathbb{R}^n \). Starting from a certain initial condition \( x(0) \in \mathbb{R}^n \), left to its own devices, the system will reach a stable orbit \( A_i \). We will show that both periodic modulation \( u_c(t) \) and positive feedback \( kx_j \) (where \( k > 0 \) is the feedback strength) simultaneously applied to the system parameter as

\[ p = p_0 + u_c(t) + kx_j \tag{1.2} \]

are able to transform the multi-stable system to a monostable one at orbit \( A_i^* \) with the same dominant frequency \( f_i \) as any preselected state \( A_i \). In equation (1.2), \( p_0 \) is the parameter value prior to the control, \( u_c(t) = m_c \sin(2\pi f_c t) \) is the additional harmonic modulation with amplitude \( m_c \) and frequency \( f_c \) close to \( f_i \) of the selected orbit \( A_i \) being either periodic or chaotic. We will show how the combination of the external modulation and the positive feedback converts a multi-stable system with coexisting either periodic or chaotic orbits with pronounced dominant frequencies into a monostable system. Note that our control method is invasive and cannot be applied to systems with coexisting steady-state attractors.

Intuitively, the physical mechanism underlying our method can be understood as follows. In a non-autonomous forced system, the coexisting stable periodic orbits are induced by the driving modulation and their frequencies are exactly subharmonics of the driving frequency.
Evidently, the external modulation \( u_c(t) \) at one of these subharmonic frequencies \( f_c = f_i \) gets in resonance with this subharmonic frequency \( f_i \). Due to the resonant interaction, the external forcing improves stability of the orbit \( A_i^* \) induced by the control modulation. Simultaneously, the feedback, depending on the sign of \( k \), introduces a parabolic potential on the top of the system’s phase space structure to favour \( A_i^* \). Depending on how the parameter enters, a different potential might be created, so that the orbit \( A_i^* \) remains unique. As it is not possible to obtain analytical solutions, the above speculations remain hypothetical only based on our numerical simulations.

Although the final attractor \( A_i^* \) in the presence of the control equation (1.2) is not exactly the same as the original orbit \( A_i \), both attractors possess the same dominant frequency in their power spectra and have a similar waveform; even though the outcome has a larger size. It should be noted that, in a driven system, feedback alone cannot annihilate the orbit induced by the driving force (i.e. the period 1), but together with additional modulation it makes it happen. Unlike the Kapitza pendulum [32] and methods for dynamic stabilization of unstable states by parameter modulation [33–36], in our method we deal with already stable orbits, and the control aim is to destabilize undesired orbits and leave a single orbit.

The rest of the paper is organized as follows. First, in §2, we apply our method to a non-autonomous system, namely to a fibre laser model with coexisting periodic orbits, test the method experimentally and compare experimental results with numerical simulations. Then, in §3, we extend our method to an autonomous system modelled by a Rössler-like oscillator with two coexisting chaotic attractors. Finally, our main conclusions are given in §4.

2. Non-autonomous system

(a) Multi-stable fibre laser with coexisting periodic orbits

In order to demonstrate how our method works in a real multi-stable system, we apply our approach to a diode-pumped erbium-doped fibre laser (EDFL) as an archetypical system with coexisting periodic orbits. The dynamics of the EDFL is described by the following rate equations [37,38]:

\[
\begin{align*}
\frac{dP}{dt} &= \frac{2L}{T_r} P (r_o \alpha_0 [N(\xi_1 - \xi_2) - 1] - \alpha_{th}) + P_{sp} \\
\frac{dN}{dt} &= -\frac{\sigma_{12} r_o P}{\pi r_0^2} (N \xi_1 - 1) - \frac{N}{\tau} + P_{pump},
\end{align*}
\]

where \( P \) is the intracavity laser power, \( N = (1/n_0 L) \int_0^L N_2(z) \, dz \) is the averaged (over the active fibre length \( L \)) population of the upper lasing level, \( N_2 \) is the upper level population at the \( z \) coordinate, \( n_0 \) is the refractive index of a ‘cold’ erbium-doped fibre (EDF) core, and \( \xi_1 \) and \( \xi_2 \) are parameters defined by the relationship between cross sections of ground-state absorption \( (\sigma_{12}) \), return stimulated transition \( (\sigma_{21}) \) and exited-state absorption \( (\sigma_{23}) \). \( T_r \) is the photon intracavity round-trip time, \( \alpha_0 \) is the small-signal absorption of the erbium fibre at the laser wavelength, \( \alpha_{th} \) accounts for the intracavity losses on the threshold, \( \tau \) is the lifetime of erbium ions in the excited state, \( r_o \) is the fibre core radius, \( w_0 \) is the radius of the fundamental fibre mode, and \( r_w \) is the factor that conveys the match between the laser fundamental mode and erbium-doped core volumes inside the active fibre. The spontaneous emission into the fundamental laser mode is derived as

\[
P_{sp} = N \frac{10^{-3}}{\tau T_r} \left( \frac{\lambda_g}{w_0} \right)^2 \frac{r_0^2 \alpha_0 L}{4 \pi^2 \sigma_{12}},
\]

where \( \lambda_g \) is the laser wavelength. The pump power is expressed as

\[
P_{pump} = P_p \frac{1 - \exp[-\alpha_0 \beta L(1 - N)]}{N_0 \pi r_0^2 L},
\]
\[ P_p = p_0[1 - m_d \sin(2\pi f_d t) + m_c \sin(2\pi f_c t) + kP]. \] (2.4)

In figure 1, we demonstrate a glimpse of the results with the time series, which illustrate the efficiency of our method in making the laser monostable at any of the possible periodic orbits. No matter from which initial state we started, the control destabilizes all attractors except one \( A_i^* \) with dominant frequency \( f_i \) of the preselected orbit \( A_i \), thus making the laser monostable.

To reveal the mechanisms underlying our method, we consider separately the effects of the harmonic modulation and the positive feedback. Figure 2 shows the bifurcation diagrams of the laser peak intensity for every coexisting attractor when only harmonic modulation with frequency \( f_c = f_i \) is applied. Although the peak amplitude varies from pulse to pulse, the phase is locked by...
Figure 2. Numerical bifurcation diagrams of laser peak intensity versus modulation depth when only additional harmonic modulation (without feedback) is applied with (a) $f_c = f_1$, (b) $f_c = f_3$, (c) $f_c = f_4$ and (d) $f_c = f_5$. $k = 0$, $m_d = 1$, $f_d = 80$ kHz. The initial conditions are randomly varied. The inset in (b) shows the time series for the period-15 attractor. (Online version in colour.)

The control, so that the attractors are enclosed within a torus hull. As the repetition rate of the laser pulses is independent of the modulation depth, the attractor periodicity is easily defined via sections through the torus.

One can see that without feedback ($k = 0$) even 100% modulation ($m_c = 1$) is not capable of making the laser monostable at an orbit with dominant frequency of any orbit prior to the control. Some subharmonic orbits with frequencies different from $f_i$ are destroyed, while other attractors arise. For instance, when $f_c = f_3$ (figure 2b), the period-1, -4 and -5 attractor branches disappear at $m_c \approx 0.1$, while new orbits appear. Interestingly, we detect stable periodic orbits with higher periods which did not exist without control, e.g. period-6 ($A_6$) and period-15 ($A_{15}$). The time series of the period-15 attractor are shown in the inset of figure 2b. As $m_c$ is increased, some states can undergo period-doubling bifurcations and even become chaotic, for example the branches starting from the period-4 orbit in figure 2c and from the period-5 orbit in figure 2d.

On the other hand, the feedback alone ($m_c = 0$) allows monostability for the period-1 attractor only. As seen from the bifurcation diagram in figure 3, the increasing feedback strength consequently destabilizes period-5, -4 and -3 orbits, so that the single period-1 ($A^*_1$) attractor remains. Even though we can reach a monostable system, neither modulation nor feedback by itself gives the selection option to the researcher.

The numerical state diagrams in figure 4 illustrate the combined effect of the harmonic modulation and the positive feedback. Each diagram represents the green region where only one attractor exists. Note, that, in other (blue) regions, monostability is also possible, but for other attractors. For example, without control modulation ($m_c = 0$) or for very small $m_c$, a single period-1 attractor is observed for $k > 0.4$. 

![Bifurcation diagrams](attachment:image.png)
Figure 3. Numerical bifurcation diagrams of laser peak intensity versus feedback strength when no additional external modulation is applied. $m_c = 0, m_d = 1, f_d = 80$ kHz. The initial conditions are randomly varied. (Online version in colour.)

Figure 4. Numerical state diagrams in $(k, m_c)$-parameter space when control modulation at frequency (a) $f_1$, (b) $f_3$, (c) $f_4$ and (d) $f_5$ is applied. Monostability is found in the light regions. (Online version in colour.)

To demonstrate that the blue pixels inside of the green regions in figure 4 do correspond to multi-stable regimes, we calculate the bifurcation diagrams for $f_c = f_3$ using $m_c$ as a control parameter for three different feedback strengths ($k = 0.1, 0.25, 0.5$) and randomly varying initial conditions. From these diagrams in figure 5, one can see that the system is monostable at the period-3 orbit within a certain range of $m_c$ and the region of monostability enlarges as $m_c$ increases, while the peak intensity becomes higher. The alternation of multi-stable and
Figure 5. Numerical bifurcation diagrams for $f_c = f_3$ with $m_c$ as a control parameter at (a) $k = 0.1$, (b) 0.25 and (c) 0.5, calculated for 30 randomly varied initial conditions. The monostable and multi-stable regions alternate as $m_c$ is varied. (Online version in colour.)

Figure 6. Basins of attraction of period-1, period-3, period-4, period-6 and period-15 orbits for $f_c = f_3$ at $k = 0.1$ and (a) $m_c = 0.07$, (b) 0.12, (c) 0.49 and (d) 0.97. (Online version in colour.)

monostable regimes, as $m_c$ is varied, is evidently seen in the basins of attraction of the coexisting states shown in figure 6. One can see that the system is monostable at the $A^*_3$ attractor for $k = 0.1$ and $m_c = 0.12$ (figure 6b). The comparison of the bifurcation diagrams in figure 5 and the basins of attraction in figure 6 with the state diagrams in figure 4b justifies that the appearance of the blue pixels inside the green regions in figure 4 is not a numerical artefact.

The efficiency of our method in controlling the number of coexisting attractors is demonstrated in figure 7, where we plot the basins of attraction of the periodic orbits when $f_c = f_5$. While for very
Figure 7. Basins of attraction of coexisting periodic orbits in the laser with control modulation at $f_c = f_i$ for (a) $m_c = 0.0065$, $k = 0$, (b) $m_c = 0.168$, $k = 0.5$, (c) $m_c = 0.79$, $k = 0.5$ and (d) $m_c = 0.9$, $k = 0.5$. (Online version in colour.)

small control amplitude $m_c = 0.0065$ without feedback ($k = 0$), four attractors coexist (figure 7a), for larger amplitude $m_c = 0.168$ and with feedback $k = 0.5$, three attractors coexist (figure 7b). For the same feedback and $m = 0.79$, two attractors coexist (figure 7c), and finally for $m = 0.9$, only one period-5 attractor ($A^*_5$) remains (figure 7d). With the same dominant frequency and a similar waveform, it is clear that the basin of attraction of $A^*_5$ is much larger than the basin of attraction of the original attractor $A_5$, which for most applications is an asset. Note that the changes in $m_c$ in figure 7a–d are not small. From (a) to (b) $m_c$ increases 25 times, from (b) to (c) almost five times, and from (c) to (d) almost two times.

Monostability at $A^*_i$ can also be achieved if the control frequency $f_c$ is tuned a little with respect to the dominant frequency $f_i$ of a desired orbit $A_i$. However, the efficiency in this case is much lower, i.e. a stronger control (higher amplitude $m_c$) is required. The sensitivity of the system to the frequency mismatch $\Delta_1 = f_i - f_c$ is different for different attractors. When the detuning $\Delta$ is too large, the method does not work. A similar situation occurs for an autonomous chaotic system the dominant frequency of which is determined by its natural frequency.

(b) Experimental evidence

The experimental set-up is shown in figure 8. The EDFL contains the EDF and two fibre Bragg gratings (FBG1 and FBG2). The EDFL is pumped by a laser diode through the polarization controller and the wave-division multiplexer. The EDFL output is detected by a photodetector and analysed with an oscilloscope (OSC). The optical isolator in front of the detector avoids an optical feedback from the detector window to the EDFL. The signal recorded by the photodetector and amplified enters the diode current controller (DCC) of the diode pump laser. The waveform
Figure 8. Experimental set-up of the diode-pumped erbium-doped fibre laser with monostability control. EDF is the erbium-doped fibre, FBG1 and FBG2 are the fibre Bragg gratings, LD is the pump laser diode, DCC is the diode current controller, PC is the polarization controller, WDM is the wave-division multiplexer, OI is the optical isolator, PD is the photodetector, OSC is the oscilloscope, WFG1 and WFG2 are the waveform generators, and $K$ is the coupling interface. (Online version in colour.)

Figure 9. OSC traces demonstrating transitions from original period-1 to new (a) period-3, (b) period-4, (c) period-5 and (d) period-6 attractors after application of positive feedback with $k = 0.4, 0.8, 0.4, 0.4$ at 400 $\mu$s and harmonic modulation with $f_i = f_i (i = 3, 4, 5, 6)$ and $m_z = 0.3, 0.6, 0.6, 0.6 (180, 360, 360, 360 \text{ mVpp})$ at 480 $\mu$s. The upper trace is the signal applied to the diode pump current and the lower trace is the laser response. $f_d = 80 \text{ kHz}$. (Online version in colour.)

generators WFG1 and WFG2 produce periodic signals for driving and control, respectively, to be also sent to the DCC.

The OSC traces in figure 9 illustrate the experimental realization of the monostability control in the EDFL. First, we apply the positive feedback and then harmonic modulation with frequency
Monostability with attractor $A_i^*$ is found in the light and multi-stability in the dark regions. The dark dots in (b–d) indicate the parameters for the time series in figure 9a–c. (Online version in colour.)

Figure 10 shows the experimental state diagrams for the period-1, period-3, period-4 and period-5 attractors in space of the modulation depth and feedback strength when the control modulation with $f_c = f_i$ is applied. Although the numerical and experimental results are in good qualitative agreement, the range of experimental parameters for monostability is larger than that of numerical ones. This means that the method works better in practice than in theory. This occurs because small noise, inevitable in experiments, helps in the attractor selection, i.e. in the presence of noise, the system switches to the desired attractor more easily than without noise. The final attractor is globally stable and robust to noise because the system is monostable.

3. Autonomous system

In order to check the validity of our approach for autonomous systems, we apply our method to a piecewise Rössler oscillator with two coexisting chaotic attractors [39] characterized by distinct dominant frequencies ($f_{C_1}$ and $f_{C_2}$) in their power spectra shown in figure 11a. This oscillator is modelled as [40]

$$\frac{dx}{dt} = -\alpha_1(x + \beta y + \Gamma z),$$

(3.1)
Figure 11. (a) Power spectra and (b) phase-space portraits of a bistable Rössler-like oscillator. The coexisting $C_1$ and $C_2$ chaotic attractors are shown, respectively, by the grey and black curves. (Online version in colour.)

\[
\begin{align*}
\frac{dy}{dt} &= -\alpha_2 \left( -\gamma x + [1 - \delta]y \right), \\
\frac{dz}{dt} &= -\alpha_3 (-f(x) + z)
\end{align*}
\]

and

\[
f(x) = \begin{cases} 
0 & \text{if } x \leq 3 \\
\mu(x - 3) & \text{if } x > 3,
\end{cases}
\]

with parameters $\alpha_1 = 500$, $\alpha_2 = 200$, $\alpha_3 = 10000$, $\Gamma = 20$, $\gamma = 50$, $\delta = 14.625$ and $\mu = 15$. The system with $\beta = 10$ exhibits the coexistence of two chaotic attractors $C_1$ and $C_2$ (figure 11b). In the following, we will show that the control applied to the parameter $\beta$ as $\beta = 10 + m_c \sin(2\pi f_c t) + ky$ makes the system monostable at the attractor similar to one of the preselected states.

Figure 11 shows the power spectra and phase-space trajectories of the two coexisting chaotic attractors $C_1$ and $C_2$ in the original bistable Rössler-like oscillator (figure 11a,b). New chaotic attractors $C_1^*$ and $C_2^*$ in the monostable system have the same dominant frequencies as the original attractors and similar complexity. The difference in the attractor size appears to be due to different sizes of the basins of attraction of the original states. The destruction of $C_1$ requires much stronger external intervention as its basin of attraction is much larger than the basin of $C_2$.

The efficiency of the method for making the system monostable can be seen from the basins of attraction shown in figure 12. One can see that the basin of attraction of every final monostable state is the phase space occupied by the two original attractors.

In addition to their dominant frequencies in the power spectra, the chaotic attractors are distinguished by their complexity. The system complexity can be quantitatively characterized by the normalized permutation entropy given as [41]

\[
H[P] = \frac{S[P]}{S_{\text{max}}},
\]

where $S[P] = -\sum_{i=1}^{N} p_i \log p_i$ and $S_{\text{max}} = \log N$ with $N = D!$ being the total number of vectors over which the probability distribution $P$ is computed, and $D$ is the embedding dimension.

Using the algorithm described in [42,43], we calculate the system complexity when the control is applied. The results are shown in figure 13, where the colours indicate the normalized permutation entropy calculated by equation (3.5) in the parameter space of the feedback strength and modulation depth for two different modulation frequencies, $f_{C_1}$ (figure 13a) and $f_{C_2}$ (figure 13b). These diagrams are calculated using random initial conditions. One can see that the complexity of the final attractor of the controlled monostable system is only a little lower than that
Figure 12. Basins of attraction of chaotic attractors $C_1$ (grey area), $C_2$ (black area) and infinity attractor (white area) in (a,b) an original bistable Rössler-like oscillator and (c,d) a final monostable system under control with (c) $f_c = f_C$, $m_c = 0.5$, $k = 0.05$ and (d) $f_c = f_C$, $m_c = 0.725$, $k = 0.025$. The light curves show (a,b) the original and (c,d) final attractors. (Online version in colour.)

Figure 13. Normalized permutation entropy equation (3.5) of the Rössler-like oscillator as a function of $k$ and $m_c$ for (a) $f_c = f_C$, and (b) $f_c = f_C$. The homogeneous areas in the upper part of the diagrams indicate the regions of the same or similar complexity, meaning monostability at the $C_1^*$ and $C_2^*$ attractors. (Online version in colour.)

of the corresponding original attractor, while the difference between the perturbation entropies of the two coexisting states are pronounced. This indicates that, although our control method is invasive, the attractors in the bistable and monostable systems are very similar.

Monostability can also be distinguished by other measures; for example, by the dominant frequency in the power spectrum or the global maximum of the $z$-component, as seen from figure 11. However, only complexity indicates how much the final attractor differs from the
original one. As our system is deterministic, the random patterns in figure 13 correspond to having either $C_1$ or $C_2$ depending on the initial conditions, which means bistability. Instead, the homogeneous colour zones in the upper parts of the diagrams mean that the system complexity is almost independent of the control parameters and initial conditions, i.e. only one attractor exists.

4. Conclusion

We have shown that a multi-stable system can be converted into a monostable one by simply applying an external harmonic modulation and a positive feedback to a system parameter. The efficiency of the proposed method has been demonstrated in both non-autonomous and autonomous systems with coexisting either periodic or chaotic attractors with distinct dominant frequencies in their power spectra.

One of the main advantages of our method is its easy implementation for practical applications. Even without preliminary knowledge of the system dynamics, one can select attractors by organizing a positive feedback and tuning the generator frequency. The method can be prominent for technological applications where giant pulses are required. It may also find important applications in medicine, e.g. for designing a pacemaker to stabilize the cardiac rhythm at a desired frequency.

Data accessibility. Numerical simulations have been performed with Matlab R2012b using the Runge–Kutta method of the fourth order with a $10^{-7}$ time step and a $2^{16}$ length. The equations and all parameters are indicated in the paper. The experimental data are accessible from https://www.dropbox.com/sh/8etizikq7qekd24/AACKv8wD-KAvTBldBkw9sd2dil=0.

Authors’ contributions. R.S.E. carried out the numerical simulations and the experimental laboratory work and drafted the manuscript; A.N.P. conceived of the study, designed the study, coordinated the study and helped draft the manuscript; R.J.R. participated in the design of the study and data analysis; G.H.C. participated in laser experiments and collected experimental data. All authors gave final approval for publication.

Competing interests. We declare we have no competing interests.

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