Control of complex nonlinear wave dynamics in dissipative systems by machine learning

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Abstract

Ultrafast mode-locked fibre lasers exploiting nonlinearity in the pulse formation process are well-known to display a rich landscape of "dissipative soliton" dynamics, which results from the interplay of the nonlinearity with dispersion and dissipation. Reaching a desired operating regime in a fibre laser generally depends on precisely adjusting multiple parameters in a high-dimensional space, in connection with the wide range of accessible pulse dynamics, which is usually performed through a trial-and-error experimental procedure, due to the lack of analytic relationship between the cavity parameters and the pulse features. The practical difficulties associated with such a procedure can be circumvented by machine-learning strategies and the use of evolutionary and genetic algorithms (GAs) [1], which are well-suited to the global optimisation problem of complex functions. In this talk, we will provide a snapshot of our recent progress in the control of non-stationary nonlinear dynamics in fibre lasers by using GAs.

Breathing solitons exhibiting periodic oscillatory behaviour form an important part of many different classes of nonlinear wave systems. Recently, thanks to the development of real-time detection techniques, they have also emerged as a ubiquitous mode-locked regime of ultrafast fibre lasers [2, 3]. The excitation of breather oscillations in a laser naturally triggers a second characteristic frequency in the system, which therefore shows competition between the cavity repetition frequency and the breathing frequency. Nonlinear systems with two competing frequencies show frequency locking, in which the system locks into a resonant periodic response featuring a rational frequency ratio, and quasi-periodicity following the hierarchy of the Farey tree and the structure of the devil's staircase [4]. Whilst frequency-locking phenomena have been extensively studied theoretically and experimentally in many physical systems, all the investigations so far relate to systems where an external, accurately controllable modulation adds a new characteristic frequency to the system. In [5], we introduced an approach based on a GA for the generation of breather dynamics in fibre lasers with controlled characteristics, which relies on specific features of the radio-frequency spectrum of the breather laser output to optimise the intra-cavity nonlinear transfer function through computer-controlled polarisation control. In this talk, benefiting from this approach and further developing it to directly pinpoint frequency-locked breathers, we demonstrate that a breather mode-locked fibre laser is a passive system showing frequency locking at Farey fractions [6]. The frequency-locked states occur in the sequence they appear in the Farey tree and within a pump-power interval given by the width of the corresponding step in the devil's staircase. The breather laser may therefore serve as a simple model system to explore universal synchronisation dynamics of nonlinear systems.

First introduced in the context of oceanic waves, the concept of extreme events or rogue waves (RWs), i.e., statistically-rare giant-amplitude waves, has been transferred to other natural environments such as the atmosphere, as well as to the solid grounds of research laboratories [7]. As RWs appear from nowhere and disappear without a trace, their emergence is unpredictable and non-repetitive, which make them particularly challenging to control. Here, we extend the use of GAs to the active control of extreme events in a fibre laser cavity [8]. Feeding real-time spectral measurements into an GA controlling the electronics to optimise the cavity parameters, we are able to trigger wave events in the cavity that have the typical statistics of RWs in the frequency domain and on-demand intensity. This accurate control enables the generation of the strongest optical RWs observed so far with a spectral peak 32.8 times higher than the significant intensity threshold. The extreme spectral events observed correlate with extreme variations of the pulse energy, thus qualifying as temporal RWs as well. Importantly, significant frequency up- or down-shifting of the optical spectrum is also associated with the emergence of these waves, which suggests a new physical scenario for RW formation. Given the generality of our control strategy, which relies on the statistical defining characteristics of RWs independent of the particular physical model, it is reasonable to expect the machine-learning method used in this work to be applicable to the control of RWs in many different systems.

References

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