SENSORS

Simplified symmetry for electronics

Enhanced wireless pressure sensors can be created by relaxing parity–time symmetry conditions.

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It is now almost a century since the dawn of electronics and yet it appears that engineers and physicists have, somewhat incredibly, never really studied the dynamical properties of gain and loss beyond the obvious practical applications of amplifying signals and compensating for loss. However, the field of parity–time (PT) symmetric dynamics, which has been steadily growing since its origin within the field of quantum mechanics a few years ago[1], has shown how increasing both gain and loss in a balanced way — well beyond what would merely compensate for inherent loss — can lead to novel dynamical behaviour. Writing in *Nature Electronics*, Andrea Alù and colleagues now report a practical method of relaxing the PT symmetry condition in electronic applications and illustrate the potential of the approach by developing wireless pressure sensors with enhanced sensitivities[2]. This is the first demonstration of PT-symmetric-like electronic systems using strategies involving generic exceptional points[3] — a system condition in which frequencies become degenerate and spatial modes coalesce — and should help to move exceptional point dynamics into the mainstream of engineering tools.

Normal modes of lossless systems — Hermitian systems — have real frequencies, reflecting the conservation of total energy. If loss (or gain) is introduced, the eigenfrequencies pick up imaginary parts, translating the loss or gain into a decay or growth of the modes. These non-Hermitian systems, with weak gain or loss, exhibit dynamical behaviour that is nearly equivalent to the undamped (or amplified) system. However, the presence of symmetry in a physical system, which is often the case, can lead to extraordinary consequences. In particular, in PT-symmetric systems, gain and loss are symmetrically added into an otherwise geometrically paired lossless environment. No longer parity-symmetric (gain on left, loss on right, for example) or time-reversal symmetric (neither loss or gain behave the same with time reversed), the combination can exactly, and simultaneously, cancel. This is in spite of the spatially separated distribution of gain and loss. In contrast, in a non-symmetric system, any particular normal mode would experience gain or loss according to its spatially weighted connection to the gain or loss.

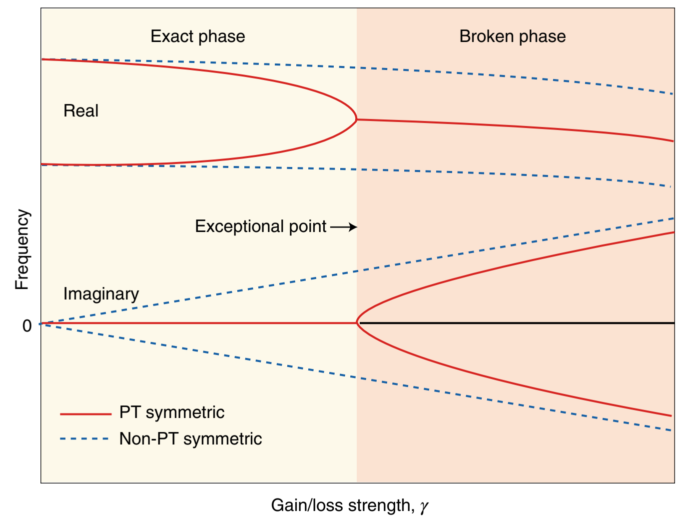

Fig. 1 | **Parity–time symmetric systems versus non-parity–time symmetric systems.** The real and imaginary eigenfrequencies for a two-mode parity–time (PT)-symmetric system (solid lines) are compared to a similar non-PT-symmetric system (dashed lines). In general, the eigenfrequencies are weakly dependent on a measure of the gain/loss strength — the non-Hermiticity parameter (γ) — where one mode grows and the other decays. The exact balance of both parity and time in the PT system creates an 'exact phase' where the modes are pseudo-Hermitian, having a zero imaginary part, and a 'broken phase' at a higher gain/loss parameter, with imaginary parts of opposite sign. The response of a PT-symmetric system has an enhanced sensitivity to many system parameters in the vicinity of an exceptional point, where a dramatic cross-over of mode eigenfrequency behaviour occurs. The behaviour is not unique to PT symmetry and can be preserved with appropriate substitution or combination with other symmetries.

This behaviour is illustrated schematically in Fig. 1, where the eigenfrequencies for a two-mode PT-symmetric system are compared to a similar non-PT-symmetric system. In the work of Alù and colleagues, the two-mode PT-symmetric system is a pair of coupled inductor–capacitor (*LC*) resonators, one of which is as a passive (lossy) sensor transducer and the other an active reader device with gain. The eigenfrequencies are, in general, weakly dependent on some measure of the gain/loss strength, or non-Hermiticity (γ), even if the gain and loss are balanced, where one mode grows and the other decays. The exact balance of both parity and time in the PT system creates an 'exact phase' where the modes are pseudo-Hermitian with a zero imaginary part, and a 'broken phase' at a higher gain/loss parameter. In the broken phase, the strength of the spatially separated gain and loss overwhelm the ability of the resonator coupling to communicate the balanced nature of the gain and loss.

Exciting and novel behaviour occurs in the vicinity of the boundary between these two phases, where an exceptional point singularity occurs. Near the PT exceptional point, there is a divergence of the sensitivity of the system to the gain–loss parameter. This is the source of the enhanced sensitivity that has previously been proposed and demonstrated in other systems, primarily optical situations such as perturbed ring resonators[4]: the exceptional point singularity translates to enhanced sensitivity of the frequencies to any parameter that modifies the exceptional point, such as the capacitance of the sensor transducer. Notably, this signal is conveniently presented to the reader device as a frequency difference. Another feature of the exceptional point is that, as the two eigenfrequencies merge into one while passing from the exact phase to the real phase, the normal modes themselves merge into one. (Technically, since the system is non-Hermitian, care needs to be taken with the meaning of 'normal modes' when they move through the non-orthogonal configuration near the exceptional point.)

Alù and colleagues — who are based at Wayne State University, Michigan Technological University and the City University of New York — have demonstrated the preservation of the dramatic PT exceptional point behaviour through the introduction of another system parameter, which allows the sensor and reader to deviate from PT symmetry as long as some other symmetry (labelled X by the researchers) is introduced to restore the 'extraordinary' system occurrence. In their sensor–reader system, neither the L or C values need to be matched. The exceptional point behaviour is restored by maintaining the equivalent of a frequency and power balance. The concept is generally applicable to other PT-symmetric systems, but is particularly transparent in the electronics regime where the long-wave limit (in which the wavelength is much larger than the size of the system) completely eliminates any need for actual geometrical symmetry. Component placement, device matching and circuit topology are irrelevant: symmetry of generic circuit functionality is the only necessary consideration.

The response of these systems is, however, sensitive to all system parameters. This means, for example, that the frequency response to the capacitance of the pressure sensor is folded into the strength of the coupling between the resonator of the reader device and the resonator of the sensor. Unless the coupling is carefully regulated, the interpretation of the pressure reading will be corrupted by instability in the proximity of the sensor to the reader device. It will be important to address this issue in order to exploit the full potential of enhanced exceptional point sensitivities and create practical sensors. But as engineers become more familiar with exceptional point dynamics, it should be possible to take advantage of the full dynamical information available. With the ubiquity of microcontrollers, it is possible to imagine interrogating the sensor–reader system in the time domain, rather than the steady state. Continual application of probe pulses and subsequent analysis of the beat waveform of the oscillator pair normal mode superposition would allow continual monitoring of the coupling. This should allow for both feedback control of the exceptional point, and the unfolding of the sensor capacitance from the coupling strength. ❐

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