Morphological analysis of out-of-Equilibrium Bose-Einstein condensates based on image processing

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Bose-Einstein condensates (BECs) are a unique state of matter achieved by cooling a gas of neutral atoms to extremely low temperatures. BECs have been the subject of intense research in recent years due to their potential applications in quantum computing such as the simulation of complex quantum systems and developing ultra-precise sensors, to mention a few. BECs are highly sensitive to external perturbations, which may cause them to radically change their shape and size. As a result, it can be difficult to accurately determine these properties. In fact, investigating most features of out-from-equilibrium Bose-Einstein condensates is challenging, and it may require more elaborated digital image processing techniques than those already in use. From the beginning, the study of perturbed BECs was mainly based on the determination of the momentum density distribution. However, we realized the possibility of expanding the scope of the investigation, as well as the volume of interesting results if we could bring more general concepts to the analysis, which are widely used in the image processing community. In addition, it was noted that the mathematical basis underlying the algorithms is quite general and independent of the type of image studied. The morphological changes observed in the perturbed atomic clouds resulting from the excitation amplitude were observed in a consistent manner, as shown by the results. And the atomic clouds spatial spread under free fall shows some symmetry, better observed under certain conditions. Our recent investigation of Pearson's correlation coefficients and fractal dimensions revealed good consistency, which suggests that the evolution to turbulent states is taking place beyond certain degrees of perturbation. This work was funded by the São Paulo Research Foundation (FAPESP) under the grants: 2013/07276-1, 2014/50857-8, and 2022/15348-1; and, by the National Council for Scientific and Technological Development (CNPq) under the grant 381381/2023-4.