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The mathematics of prey detection in spider orb-webs

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Spider webs are one of nature's most fascinating manifestations. Many spiders extrude proteinaceous silk to weave sticky webs that ensnare unsuspecting prey who venture into their threads. Despite their elasticity, these webs possess incredible tensile strength. In recent years, scientists have expressed increased interest in the spider orb-web as a biological-mechanical system. The web's sensory mechanisms are especially fascinating, given that most web-weaving spiders—regardless of their vision level—use generated vibrations to effectively locate ensnared prey.

"The spider orb-web is a natural, lightweight, elegant structure with an extreme strength-to-weight ratio that is rarely observed among other structures, either natural or manmade," Antonino Morassi said. "Its primary functions are catching prey and gathering sensory information, and study of the mechanisms that guide these processes through web vibration has been one of the main research goals in the field."

To understand the mechanics of orb-webs, researchers have previously utilized simplified patterns of wave propagation or relied upon numerical models that reproduce a spider web's exact geometry via one-dimensional elements. While these numerical models adequately handle wind, prey movement, and other sources of vibration, they fall short of providing insight into the physical phenomena responsible for web dynamics. In an article publishing this week in the *SIAM Journal on Applied Mathematics*, Morassi and Alexandre Kawano present a theoretical mechanical model to study the inverse problem of source identification and localize a prey in a spider orb-web.

Due to structural interconnectivity between the circumferential and radial threads, vibrations in an orb-web spread laterally and move beyond the stimulated radius. This observation led Kawano and Morassi towards realistic mechanical models that measure a fibred web's two-dimensionality, rather than more limiting one-dimensional models. "There was no mechanical model—even a simplified one—that described the web as it really is: a two-dimensional vibrating system," Morassi said. "We decided to use a continuous membrane model since theoretical models often permit a deeper insight in the physical phenomena through analysis of the underlying mathematical structure of the governing equations." These equations are also useful in identifying the most relevant parameters that dictate a web's response.

The authors classify their model as a network of two intersecting groups of circumferential and radial threads that form an uninterrupted, continuous elastic membrane with a specific fibrous structure. To set up the inverse problem, they consider the spider's dynamic response to the prey's induced vibrations from the center of the web (where the spider usually waits). For the sake of simplicity, Kawano and Morassi limit the model's breadth to circular webs. The geometry of their model allows for a specific fibrous structure, the radial threads of which are denser towards the web's center.

The researchers note that the minimal data set to ensure uniqueness in the prey's localization seems to accurately reproduce real data that the spider collects right after the prey makes contact with the web. "By continuously testing the web, the spider acquires the dynamical response of the web approximately on a circle centered at the web's origin, and with radius significantly small with respect to the web dimensions," Kawano said. "Numerical simulations show that identification of the prey's position is rather good, even when the observation is taken on the discrete set of points corresponding to the eight legs of the spider."

Ultimately, the authors hope that their novel mechanical model will encourage future research pertaining to nearly periodic signals and more general sources of vibration. They are already thinking about ways to further expand their model. "We believe that it may be of interest to generalize the approach to more realistic geometries—for example, for spider webs that deviate a little from the circular axisymmetric shape and maintain only a single axis of symmetry," Morassi said. "Furthermore, here we considered the transversal dynamic response caused by orthogonal impact of a prey on the web. In real-world situations, impact can be inclined and cause in-plane vibrations to propagate throughout the web. The analysis of these aspects, among others, may provide novel and important insights, not only for the prey's catching problem but also for bioinspired fibrous networks for sensing applications involving smart multifunctional materials."

More information: Kawano, A., & Morassi, A. (2019). Detecting a prey in a spider orb-web. *SIAM J. Appl. Math*. To be published.

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