Effect of eccentricity on sensing in spider web inspired cable nets

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Abstract. Spider webs are multifunctional tools that, besides capturing prey, monitor vibration in the web to localize the prey. Spiders obtain an evolutionary benefit from improving monitoring because better information processing leads to more successful captures, leading to higher chances for survival. Based on this, combined with the costly energy requirements of signaling, biologists observe that the spider's web operates as an extended cognition of the spider's central nervous system. Here an extended cognition means that the web filters signals to make decoding information easier. Spider webs contain characteristic design patterns, such as an eccentric location of the central hub. This paper investigates how this eccentricity enables a spatially dependent dynamic response of web-like structures, potentially enabling extended cognition. Modeling consists of modal analyses in a Finite Elements Model on web-like structures where a mass is sequentially moved across all nodes. This yields the natural frequencies of the structure depending on the mass location. Analysis shows that the natural frequency forms patterns based on the mass location, and more importantly, it shows how these patterns become more intricate by including eccentricity. The resulting maximum change in natural frequency grows as the eccentricity in the design grows. This shows that eccentricity influences the dynamic response, hence indicating that eccentricity could enable the web's extended cognition. The numerical model of spider web-inspired structures can investigate the effects of the geometry on any network-like structures besides spider webs. The authors believe the model can be utilized for impact/anomaly detection on network-like structures.

1. Introduction

Nature offers many structural and material designs for performing multiple functions simultaneously such as sensing [1], energy harvesting [2], thermal regulation [3], and actuating [4]. Nature's geometrically-driven multifunctional designs have led to engineering bio-inspired structures not only to bear loads, but also to morph, sense, actuate, and monitor their structural health, for many applications in medicine, aerospace, transportation, and electronics. In this paper, our study was focused on revealing the vibratory behaviors of cable-network designs with eccentricities inspired by spider-web off-center hubs, fig. 1. The web has a central hub, from which radials span outwards. The vertical asymmetry, or eccentricity, can be identified by observing that this hub is above the geometric center of the web. Remarkably, our findings appear to support the extended cognition hypothesis posed by biologists in recent publications [5]. Our results show that there is a strong interplay between the spider-web asymmetric designs (eccentric hubs) and the spiders web's extended cognition. Here an extended cognition means that the web filters signals to make decoding information easier.

Biologists speculated that spiders utilize their web as extended cognition to supplement their limited central nervous system— since their relative brain sizes are small for processing a sensory-rich of the web environment [5, 6]. The extended cognition of the web refers to its ability to filter signals to decode vibration information efficiently. Through vibrations in the web, a spider could monitor changes in the mass of the web to determine the presence of prey and detect its location. To this end, the present study focused on modeling the effect of the central hub degree of eccentricity on the vibration behaviors of a steel cable network with and without point mass. The intent of the point mass was to simulate the presence of prey. The study's main objective was to examine the principle of extended cognition as a tool for identifying the location of the mass. Our findings show that the geometric eccentricity of the hub influenced the vibration response in web-like cable network.

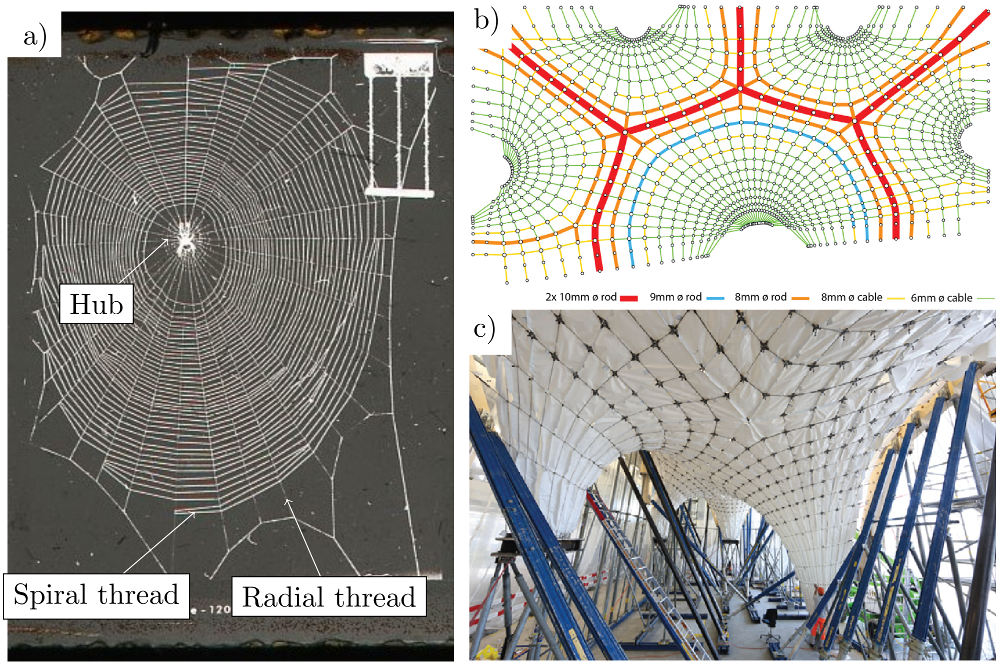


Figure 1: a) An eccentric orb web of *Araneus diadematus* taken from Witt et al [7]. Nomenclature is in accordance with Zschokke (1999) [8]. b) and c) A cable net form work from Echenagucia et al. [9] that has potential to use multifunctionalities similar to those found in spider webs.

With a few exceptions, representative spider web designs have been investigated, but the effects of the eccentricity of the central hub are underexplored. In Mortimer et al. [10] the dynamics of the web were investigated based on a traced images of a spider web. Later, they attempted to decode the prey location information based on web vibration on a similarly traced web [11]. They conclude that a spider could potentially use their proposed decoding approach successfully. Lott et al. [12] proposed a different decoding method that used modal vibration analysis in asymmetric webs. However, the sensitivity of the dynamics due to changes in the asymmetry were not explored. Jiang et al. [13] have investigated the dynamic response of symmetric spider webs subjected to impact. They describe how damage in the web reduces its ability to absorb energy, as well as how the dynamics change due to damage. Using only non-eccentric web designs Otto et al. [14] showed the effects of the number of spiral turns and radials, as well as the radial tension in the web, on the web vibration. They did not, however, investigate how well their localizing method performs based on changes in the web designs. The results show that the information gathered by a spider at the hub is sufficient to find the impact region. This meant that even though the dynamics of spider webs were investigated and attempts were made for mass localization based on vibrations, the effects of the hub location on the web dynamics are not well understood. A promising paper by Dal Poggetto et al. [15] evaluated how the modal dynamics of a spider web are affected by a movable mass in the web; however, the effects of changes in the geometry, such as eccentricity, were not investigated. Additionally, only changes in the first natural frequency were included, but no higher resonances. Insights can be gained into how the eccentricity of a hub could affect the vibration signals in the web by starting with estimating the resonant frequencies of a string, which can be expressed as [16]:

$$\omega_n = \frac{n\,c\,\pi}{L}, \quad n = 1, 2, .. \quad \text{with } c = \sqrt{\frac{F}{m}}$$

The string length and mass are L and m, respectively. The tension in the string is F. The computational results were obtained using a linear Finite Elements (FE) model in which a mass was moved sequentially over the nodes in the structure (fig. 3). The advantage of this approach stemmed from the number of possible model evaluations, which was enabled through automation using the Python packages COMPAS and COMPAS VIBRO [17, 18], as shown in fig. 2. The dynamics of 7434 webs were evaluated. Once for a mass attached to a different node in the FEM model of the web (1271 nodes), except for the center node and the fixed nodes at the boundary (31 boundary nodes). This was accomplished for six different web geometries, where each had a different eccentricity level.

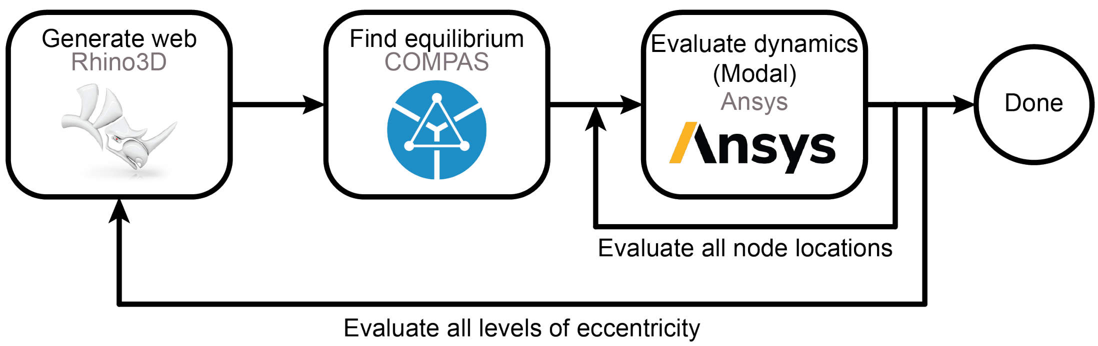


Figure 2: Modeling approach. Web geometries were generated using Rhino3D, the web in equilibrium is found using the Force Density Method as implemented by the python library COMPAS, and the dynamics of the system are evaluated using Ansys APDL.

2. Characterizing the dynamics of webs

2.1. Introducing eccentricity into web designs

To study the effect of eccentricity in spider webs, a web was designed that incorporates various levels of eccentricity. The number of radials (n_r) and concentric circles (n_c) in this web are chosen to be 31 and 13, respectively, and are chosen to resemble typical webs in nature [19]. This web can be made to be eccentric by choosing the upper nine radials to have a higher tension or lower initial lenght than the other radials. The equilibrated web would have its center pushed

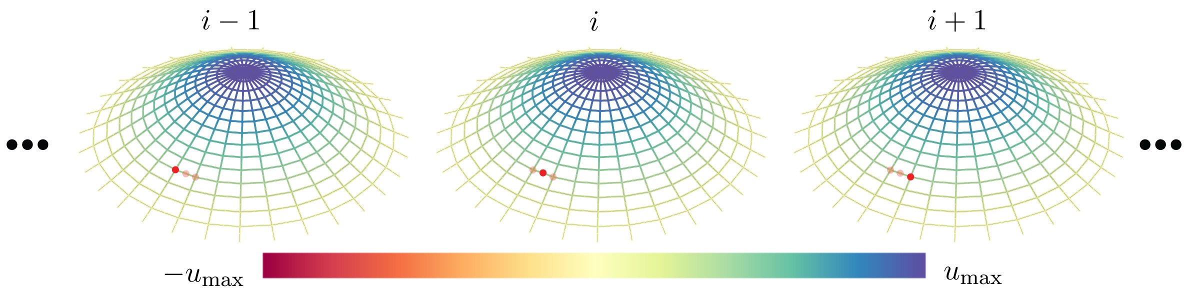


Figure 3: In the modeling approach a mass (red dot) representing the prey is moved to a new node every step. This finds the mode shapes (ϕ) and natural frequencies (ω_n) for all node locations.

upwards. The level of eccentricity was defined as (upper − lower)/(upper + lower), where upper is the distance between the top of the web and the hub of the web and lower the distance between the bottom of the web and the hub. This definition is in accordance with the definition used in previous research [20, 21, 22]. The radius of the web is chosen to be 10 m. Note that this dimension does not resemble webs in nature, but is in the order of magnitude of the cable-form networks.

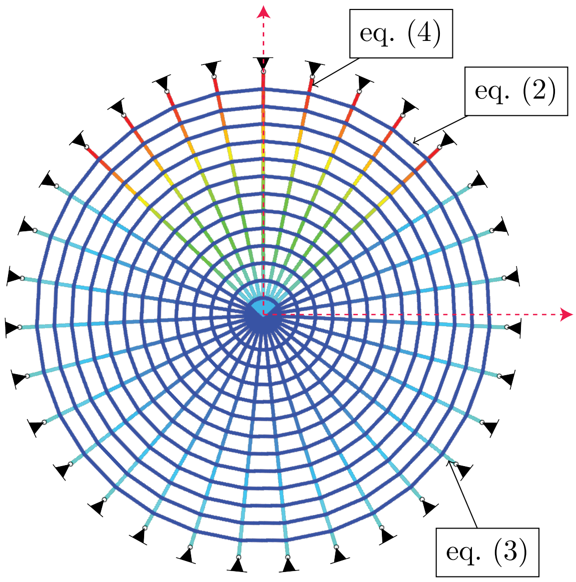
2.2. Applying the Force Density Method (FDM)

The shape of the spider webs was determined using the Force Density Method (FDM)[23]. FDM has been used in the past as a form-finding method in the design of cable-nets, tensile fabric roofs, and other types of equilibrium structures. Consider a network of bars capable of resisting only axial forces F, connected by nodes, some subjected to external forces p and some considered anchored. For the network to be in equilibrium, the following equation must be satisfied for all of the free nodes:

$$\left[F\right]^T \cos\left[\alpha\right] + p_{x,y,z} = 0 \tag{1}$$

where $\left[F\right]$ are the internal forces of all the bars connected to a given node, $\cos\left[\alpha\right]$is the cosine of the angles between the X, Y, Z axis and the vector of the bar, and $p_{x,y,z}$ is the axial component of the external force on the node. The method linearizes the set of equilibrium equations for all free nodes in the network of bars, by employing a quantity called force density or tension coefficient q such that $q_i = F_i/l_i$, where F_i is the internal force in the i_{th} bar, and l_i is its elongated (or compressed) length. From the resulting equilibrium shape we get an updated set of X, Y, Z coordinates for all free nodes, as well as an updated set of axial forces for each bar. FDM is employed in this paper as implemented in the COMPAS [17] python library.

The input geometry and the assigned force densities of a fully symmetric web are depicted in eq. (2) to (4) in fig. 4. The force density in the concentric circles is chosen to be one. A force density gradient is defined for the radials. At the hub, the elements have a force density of one (q^{hub}) and linearly increases to four at the elements at the boundary of the web (q^{boundary}). This gradient is chosen to result in a stress profile in the webs that resembles the profile of webs in nature [24, 25]. This yields the symmetric web in equilibrium after applying the FDM in fig. 5c). The input web can be modified to include eccentricity by assigning the upper nine radials a higher force density, as depictedfig. 4 and fig. 5b). Six webs with six levels of eccentricity ($j = 1, \ldots, 6$) are achieved by multiplying the force density at the upper nine radials with a factor C_j^{ecc}, which is linearly spaced between 1 and 3. Note, that the resulting levels of eccentricity are $(\text{upper} - \text{lower})/(\text{upper} + \text{lower}) = [0.00, -0.09, -0.16, -0.22, -0.28, -0.32]$, so not linearly spaced.



$$q = 1 \tag{2}$$

$$q_c = c\frac{q^{\text{boundary}} - q^{\text{hub}}}{n_c} + q^{\text{hub}} \tag{3}$$

$$q_c = C_j^{\text{ecc}} c\frac{q^{\text{boundary}} - q^{\text{hub}}}{n_c} + q^{\text{hub}} \tag{4}$$

such that: $c = 0, \ldots, n_c$

Figure 4: Described force densities for each section of the web. c counts the concentric circles from the center outwards and n_c is the number of concentric circles

The updated set of X, Y, Z coordinates for all free nodes, as well as the set of axial forces for each element are used in the input file for the FEM model.

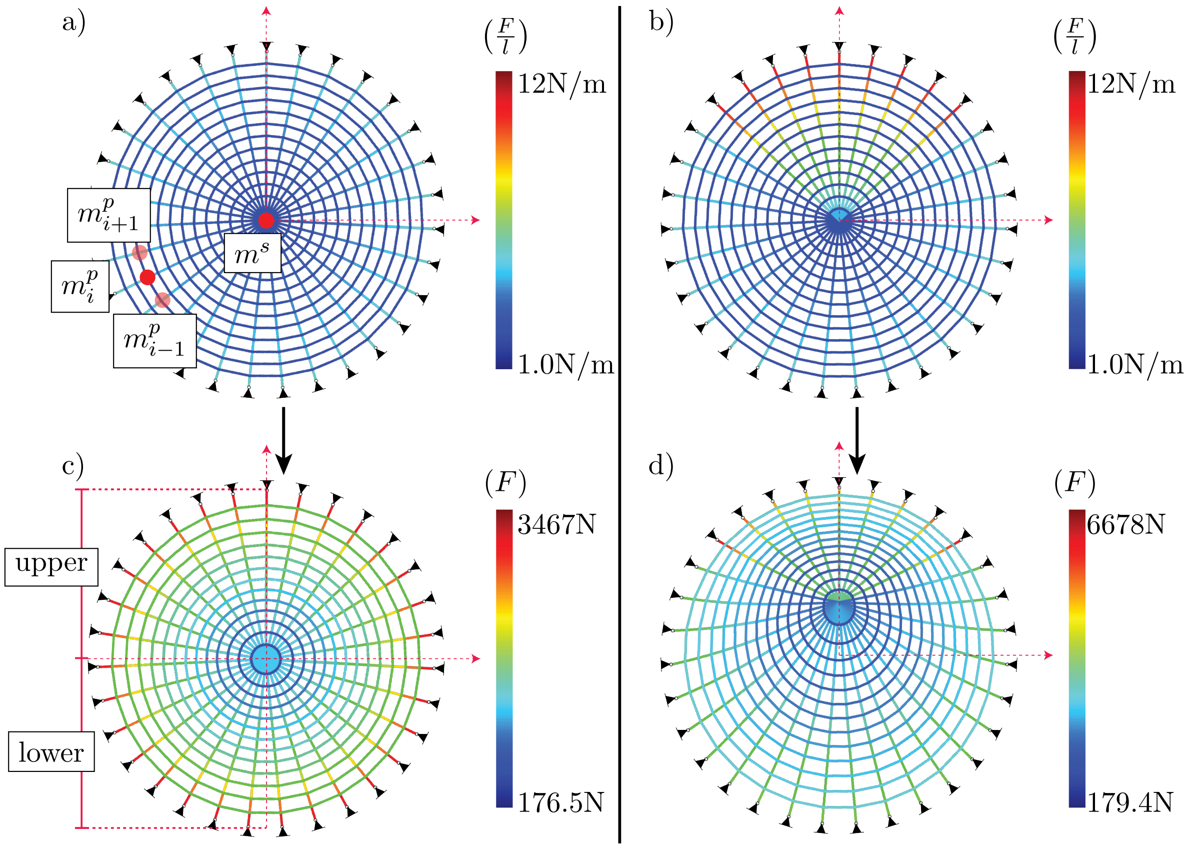


Figure 5: Geometries describing the web: a) input symmetric web ($C_1^{\text{ecc}} = 0$); b) input geometry eccentric web ($C_1^{\text{ecc}} = 0$); c) output symmetric web; and d) output geometry eccentric web. m^s and m_i^p refer to the spider and prey position respectively.

2.3. Establishing the computational experiments

The COMPAS VIBRO [18] python library is used to automate the generation of FEM models representing the web geometries, their material properties, added masses, pre-stressed states, and boundary conditions. The library is also used to export the equilibrated web geometries into Ansys Mechanical APDL for the Finite Element analysis. In Ansys the sections between every joint are split into two linear tie elements, resulting in 1271 elements. These elements represent the behavior of strings well since, like strings, they describe an axial deformation but have no out-of-plane stiffness. The 31 outermost nodes are fixed in all directions. A sensitivity analysis on the elements size is conducted on an empty web with each section split into ten instead of two elements as a sensitivity analysis on the element size. This analysis resulted in a maximum change in natural frequency of 0.74%. The material properties and order of scale used in this paper do not match that of actual spider webs. This is because this paper aims to investigate the effects of changes in the design, specifically eccentricity, and not those of the material properties. The material properties of spider silk are actual highly complex, and its inclusion is outside the scope of this paper. A nice paper that summarizes what is known of the microstructure of spider silk can be found in [26]. Even within a single web, a spider can tune the material properties between 3-28GPa dependent on what is desired [27]. In this paper, the elements are assigned the material properties of steel as set out in table 1. The elements are assigned a cross-sectional area of 0.005 m^2. To make sure that the imported geometries are in equilibrium the element tensions found in the FDM are described as pretension in Ansys.

Table 1: Material properties of steel and used cross-sectional area of threads

Young's Modulus (E) [GPa]	Density (ρ) [kg/m^3]	Poisson ratio (ν) [-]	Cross sectional area (A) [m^2]
220	7850	0.29	0.005

The total mass of the spider web-inspired network is $28.5 \cdot 10^3$ - $29.1 \cdot 10^3$ kg. Note, that the masses are not constant because the level of eccentricity affects the total volume of the geometry. When analyzing the vibration going through the web, the spider resides in the center of the web. To simulate this a mass element of 50 kg is attached to the center node. When spiders are feeling the vibration at the center they keep their legs on nearby radials [28, 29]. The interaction between the legs and radials will affect the dynamics to some degree, which is not included in this investigation for simplicity. A mass element of 100 kg, representing prey in the web-inspired network, can be attached to any node in the model. The first five natural frequencies (f_n) and Mode Shapes (ϕ_n) of the system are retrieved using a Modal Step.

Table 2: Used masses of the web, the spider at the center node, and the prey.

Mass of web (M) [kg]	Mass of spider (m_s) [kg]	Mass of prey (m_p)[kg]
$28.5 \cdot 10^3$ - $29.1 \cdot 10^3$	50	100

3. Results and discussion

Fig. 6 shows the first five mode shapes of a symmetric and an eccentric web without the added mass m^p. It can be observed that the inclusion of eccentricity distorts the symmetric mode shapes. In the symmetric web design, Modes II and III correspond to the same frequency and have the same shape, but 90 degrees rotated. Due to the symmetry of the web every mode shape that is not radially symmetric needs to show up again at the same frequency, but rotated. By breaking this symmetry the double-appearing mode shapes only appear once. This is expected to make the vibration more predictable and could help spiders with signaling.

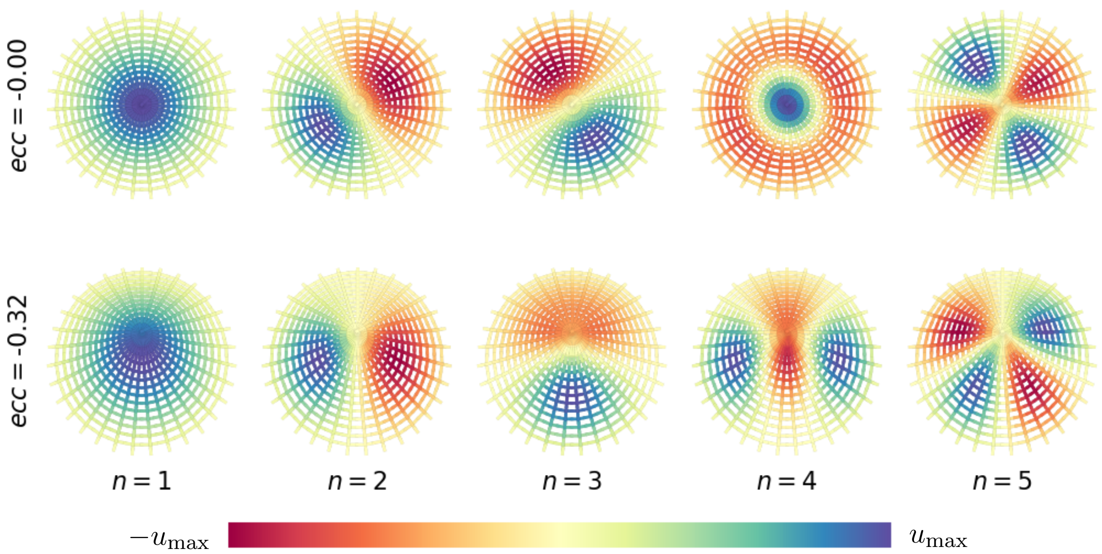


Figure 6: First five mode shapes (ϕ) of the symmetric and most eccentric web. Note that the rotational mode shapes are omitted.

The sequential modeling pipeline results in the first five natural frequencies of the system for all investigated locations of m_p and all levels of eccentricity. We define a vector of natural frequencies $\left[f_n^{(i,j)}\right]$ for each mode ($i = 1, \ldots, 5$) and each level of eccentricity ($j = 1, \ldots, 6$). For each individual mode, the natural frequencies are normalized with the lowest corresponding natural frequency found in the symmetric web:

$$\left[\Omega_n^{(i,j)}\right] = \frac{\left[f_n^{(i,j)}\right]}{\min\left(\left[f_n^{(i,1)}\right]\right)}$$

Additionally, for each individual level of eccentricity the natural frequencies are normalized by the lowest found first mode:

$$\left[\Psi_n^{(i,j)}\right] = \frac{\left[f_n^{(i,j)}\right]}{\min\left(\left[f_n^{(1,j)}\right]\right)}$$

The normalized natural frequencies that show up in the web by moving the mass around are dependent on the level of eccentricity. Its development is set out in fig. 7. We observe that the spacing between the natural frequencies increases with eccentricity. This increased spacing can potentially help spiders use individual modes for localization.

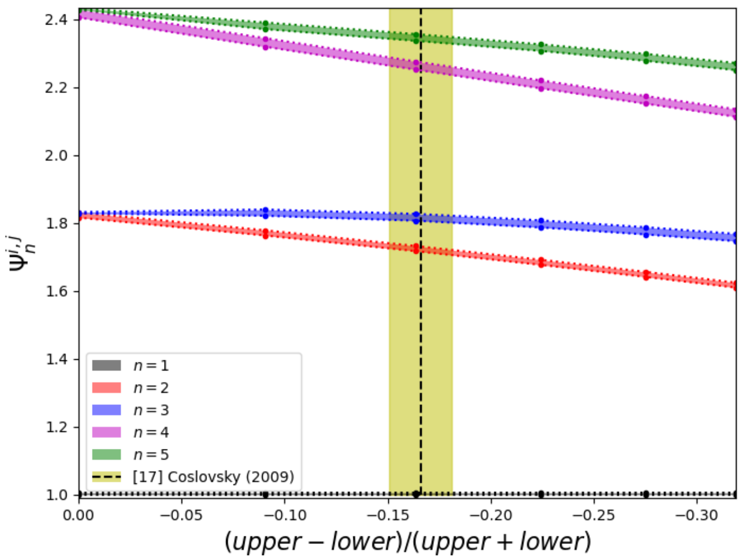


Figure 7: The full range of $\Psi_n^{i,j}$ as a function of the level of eccentricity. Reported levels of eccentricity in literature are -0.166 ± 0.015[20], and -0.167 ± 0.113[21].

In fig. 8 all normalized natural frequencies $\Omega_n^{(i,j)}$ are mapped in 5×6 separate plots. For each evaluation of the model, a colored dot is plotted at the corresponding location of m_p on top of the corresponding web.

From the frequency maps we observe that even a little bit of eccentricity in the web design results in intricate patterns showing up. These patterns suggest that including eccentricity results in location-dependent frequency responses. Whereas the symmetric web shows a similar response regardless of the location. This observation leads to the observation that spiders could use the patterns as a spatial classification of a mass m^p. The eccentricity would thus help the spider with signaling.

In previous work where the location of a mass was sequentially moved, no intricate patterns could be observed[15]. We believe that the main root cause can be found in the fact that no eccentricity was included in the studies. Apart from the catching spiral the investigated web in this paper is fully symmetric. Additionally, the fact that an unrepresentative eight radials were used in the study (in contrast to 31 in this paper) results that the largest changes in natural frequencies are found between a mass on top of one of the radials and in the middle between two radials. In this work, webs are generated with concentric circles around the center. In real webs, no concentric circles can be found, but spirals [8]. It is expected that this will slightly influence the results. A non-eccentric web with a spiral instead of concentric circles already has some asymmetry itself. Extending the reasoning from this paper, asymmetry improves signaling, this asymmetry could result in patterns as presented in this paper.

4. Conclusions and Recommendations

Spiders can potentially use the spatially depended dynamics of spider webs to decode the location of mass in the web. In this paper we present that this spatial dependence is enabled through eccentricity in the design of the webs. After including eccentricity intricate patterns show up in the natural frequency maps in fig. 8. We note that the patterns mainly show up in the higher modes, which we expect will play a larger part in signaling. Since we believe that eccentricity increases the signaling capabilities of the web, we expect that the spider webs extended cognition is enabled in part through eccentricity. Including eccentricity holds promise in increasing the sensing possibilities of spider web-inspired structures, such as the cable form works in fig. 1. It

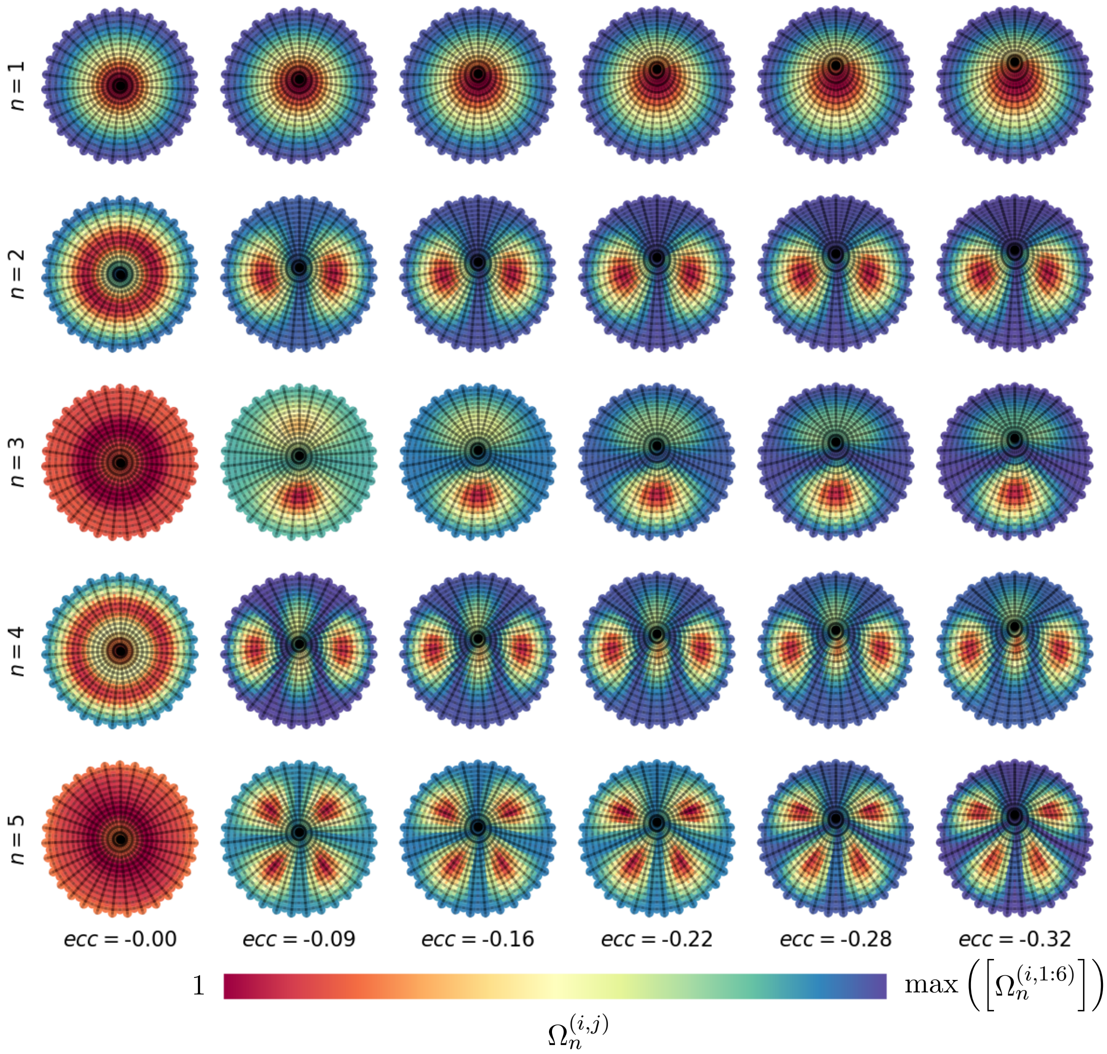


Figure 8: Mappings of normalized natural frequencies $\Omega_n^{(i,j)}$. The location of a colored dot corresponds to the location of m_p in the web.

is found that symmetric webs have some modes corresponding to the same natural frequency. The more eccentricity is included the more the natural frequencies move apart. By separating the modes further, it will be easier for sensing equipment to distinguish between the modes. This will enable using the intricate patterns of the individual modes.

A similarity is identified between the found mode shapes in this paper in fig. 6 and the frequency mappings in fig. 8. It holds promise to investigate their similarity closer. Modeling times could be reduced greatly if the two are strongly related, since only mode shapes of empty webs would need to be extracted to find the frequency mapping. This investigation is limited to a modal analysis but can be extended with a Steady State analysis, or with simulations in the time domain. This would yield significant insight into the real dynamics of the web, which could yield a deeper understanding of how eccentricity affects signaling. These additional analysis steps can give insight into the dynamics of prey impacting the web, and into plucking. Where in plucking, spiders send out their own signals by jerking the web.

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