

Compliant Serial 3R Chain with Spherical Flexures

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Abstract A spherical flexure is a special kind of compliant hinge specifically conceived for spherical motion. It features an arc of a circle as centroidal axis and an annulus sector as cross-section, circle and annulus having a common center coinciding to that of the desired spherical motion. This paper investigates a compliant spherical 3R open chain that is obtained by the in-series connection of three identical spherical flexures having coincident centers and mutually orthogonal axes of maximum rotational compliance. The considered spherical chain is intended to be used as a complex flexure for the development of spatial parallel manipulators. The compliance matrix of the proposed chain is first determined via an analytical procedure. Then, the obtained equations are used in a parametric study to assess the influence of spherical flexure geometry on the overall stiffness performances of the considered 3R open chain.

1 Introduction

Compliant mechanisms (CMs) are a special kind of articulated systems in which motion, force or energy are transferred or transformed through the deflection of flexible members (hereafter briefly referred to as “flexures” or “flexural hinges”) [10]. Thanks to the absence (or reduced use) of traditional kinematic pairs, which are

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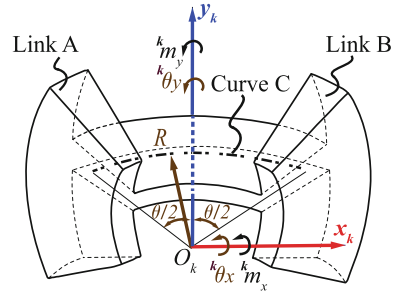
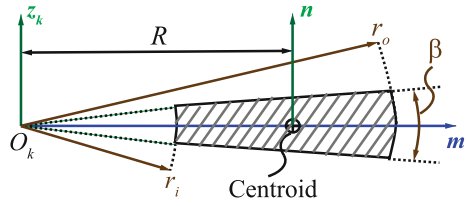
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instead based on mating surfaces, CMs are almost not affected by wear, friction and backlash, and only require minimal maintenance with no need of lubrication. Due to their hinge-less nature, CMs can be manufactured in a single piece (for instance via laser or water jet cutting, electrical discharge machining or additive manufacturing), thereby reducing number of parts, assembly needs and, thus, manufacturing costs. With the above-mentioned features, CMs are ideal to work in vacuum, contamination-free, wet or dirty environments and in devices requiring resistance to shocks and silent operation. Common applications of CMs span high-precision manufacturing [27, 36], minimally invasive surgery [9, 18] and micro-electromechanical systems (MEMS) [1, 30].

As regards the existing literature, several studies have been devoted to the design, the characterization and the comparative evaluation of different flexure geometries and CMs formed therewith (see e.g. [14, 21, 31, 35]). In particular, most of these devices have been specifically conceived for the generation of planar motions only, out-of-plane displacements being regarded as *parasitic effects* to be minimized when possible [13]. On the other hand, despite the huge potentialities, exploitation and study of CMs specifically conceived for spatial motions have been much more rare (see e.g. [3–5, 20, 26, 28, 32, 34, 39]). Within this scenario, the development of Spherical CMs (SCMs) has recently attracted the attention of several researchers. SCMs are an important class of flexure-based spatial CMs in which all points of the end-link are ideally constrained to move on concentric spherical surfaces that are fixed with respect to the grounded link. In particular, the in-series ensemble of two or three compliant revolute (R) joints (of either planar notch, planar leaf spring or straight torsion beam type) with orthogonal and intersecting axes has been proposed in [8, 17, 19, 37] to conceive compliant spherical 2R or 3R serial chains to be used as compliant universal or spherical joints for the development of Cardan's [33] and Double-Hooke's couplings [17] and of spatial parallel manipulators [4, 5, 20, 26, 28, 32, 34, 39]. In these applications, the use of compliant spherical 2R or 3R serial chains in place of the axial-symmetric notch primitive flexure is usually preferred owing to the more limited ranges of motions and larger stress concentrations of this latter. The connection of four, five, six or eight bars with an equal number of compliant revolute joints (of either straight crease or lamina emergent torsional type) with intersecting axes has been considered in [6, 7, 38] for the development of 4R, 5R, 6R or 8R closed single-loop lamina-emergent SCMs, as well as arrays thereof (including the six bar Watt's and Stephenson's linkages), to be used in origami-inspired foldable systems such as pop-up books, industrial packaging and deployable devices. Planar notch and straight torsion beam flexures have been used in [19] to develop an actuated miniature 3-CRU (C and U denoting cylindrical and universal joints respectively) spherical parallel CM for the orientation of parts and tools in space. The in-parallel connection of three symmetrically placed spherical 3R serial chains employing either lamina emergent straight torsion beam or notch flexures has been proposed in [11, 29] for the development of 3-(3R) spherical parallel CMs with flat initial state to be used in compact pointing devices such as in MEMS beam-steering mirrors or medical instruments.

Fig. 1 Spherical flexures**Fig. 2** Cross section properties of SFs

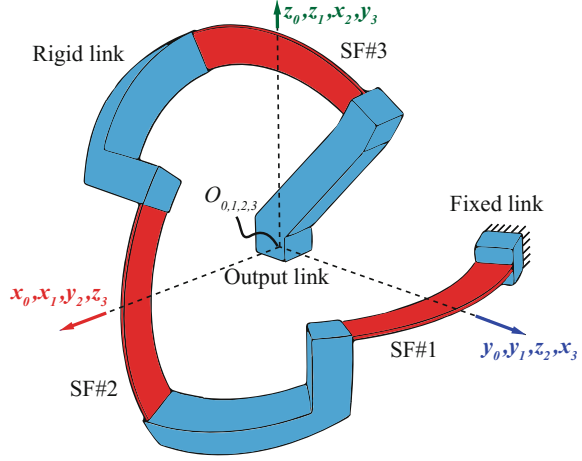
In all the above-mentioned studies, the considered SCMs have been obtained by employing compliant revolute flexures specifically conceived for planar motion applications. In contrast to this, Circularly-Curved Beam Flexures (CCBFs) with constant cross-section and featuring lower rotational rigidity along the radial direction have been proposed in [12, 22] for the development of SCMs with improved spherical motion capabilities. Among these CCBFs, those with annulus sector cross-section as depicted in Figs. 1 and 2, hereafter referred to as Spherical Flexures (SFs), have recently been demonstrated among the most effective ones in reducing the drift of the desired center of spherical motion under the combined action of torques and forces [25].

In this context, this paper investigates the use of SFs for the development of compliant spherical 3R serial chains to be used as SCMs or as spherical complex flexure components for spatial CMs with either serial or parallel architecture. As depicted in Fig. 3, the considered spherical chains are obtained by the in-series connection of three identical SFs that are arranged in space so as to share the same center of curvature and have mutually orthogonal axes of maximum rotational compliance. In particular, analytical results are provided to characterize the compliance behavior of the considered chain in 3D space as a function of flexure geometric parameters.

2 Formulation

A spherical flexure connecting the rigid links A and B is depicted in Fig. 1. It is a solid of revolution characterized by an annulus sector cross-section with inner and outer radii, r_i and r_o , and subtended angle β (see Fig. 2), an axis of revolution z_k

Fig. 3 SF-based compliant spherical 3R open chain



passing through the center O_k of the annulus and orthogonal to the cross-section axis of symmetry, $\mathbf{m}$, (see Fig. 1), and revolution angle θ (which describes the flexure length). Cross-section dimensionless parameters, β and w^* ($w^* = \frac{r_o - r_i}{r_o}$), are such that its smaller area moment of inertia is in the direction of the $\mathbf{m}$ axis. Assuming link A being clamped and B free and loaded, the small deflection behavior of the flexure about its unloaded configuration can be described by the following relation [23]:

$${}^k \mathbf{s} = \begin{bmatrix} {}^k \mathbf{u} \\ {}^k \boldsymbol{\theta} \end{bmatrix} = \begin{bmatrix} {}^k \mathbf{C}_{uf} & {}^k \mathbf{C}_{um} \\ {}^k \mathbf{C}_{\theta f} & {}^k \mathbf{C}_{\theta m} \end{bmatrix} \cdot \begin{bmatrix} {}^k \mathbf{f} \\ {}^k \mathbf{m} \end{bmatrix} = {}^k \mathbf{C} \cdot {}^k \mathbf{w} \quad (1)$$

where ${}^k \mathbf{s}$ is composed of an incremental translation ${}^k \mathbf{u} = [{}^k u_x \ {}^k u_y \ {}^k u_z]^T$ and an incremental rotation ${}^k \boldsymbol{\theta} = [{}^k \theta_x \ {}^k \theta_y \ {}^k \theta_z]^T$, ${}^k \mathbf{w}$ is composed of an incremental force ${}^k \mathbf{f} = [{}^k f_x \ {}^k f_y \ {}^k f_z]^T$ and an incremental torque ${}^k \mathbf{m} = [{}^k m_x \ {}^k m_y \ {}^k m_z]^T$, whereas ${}^k \mathbf{C}_{uf}$, ${}^k \mathbf{C}_{um}$, ${}^k \mathbf{C}_{\theta f}$, ${}^k \mathbf{C}_{\theta m}$ are three-dimensional matrices composed of entries with dimensions [m/N], [l/N], [rad/N], and [rad/Nm] respectively.

As a consequence, ${}^k \mathbf{C} \equiv {}^k \mathbf{C}_{ij}$ is a 6×6 matrix with entries of non uniform physical dimensions, the submatrices ${}^k \mathbf{C}_T = [{}^k \mathbf{C}_{uf} \ {}^k \mathbf{C}_{um}]$ and ${}^k \mathbf{C}_R = [{}^k \mathbf{C}_{\theta f} \ {}^k \mathbf{C}_{\theta m}]$ relating the external wrench to the resulting translations and rotations respectively.

The expression of Eq. 1 is frame dependent. For any SF intended for spherical motion about the center of its centroidal axis circle, a suitable frame is S_k that features center at O_k and orthogonal axes x_k , y_k and z_k respectively lying on centroidal axis plane, on beam symmetry plane and along the intersection of these two planes (see Fig. 1). In this frame, indeed, sub-matrices ${}^k \mathbf{C}_{uf}$ and ${}^k \mathbf{C}_{\theta m}$ are diagonal (meaning that x_k , y_k and z_k are along the principal directions of rotational and translational compliance of the flexure), and the components of ${}^k \mathbf{C}_{uf}$ and ${}^k \mathbf{C}_{um}$ (or ${}^k \mathbf{C}_{\theta f}$) indicate how the desired center of spherical motion drifts as a consequence of applied external forces and torques.

Knowing matrix ${}^k\mathbf{C}$ for a single spherical flexure, the compliance matrix of the in-series ensemble of any number n of identical flexures can be obtained with the following formula [2]:

$${}^0\mathbf{C} = \sum_{k=1}^n {}^0\mathbf{T}_k^{-T} \cdot {}^k\mathbf{C} \cdot {}^0\mathbf{T}_k^{-1} = \sum_{k=1}^n {}^k\mathbf{T}_0^T \cdot {}^k\mathbf{C} \cdot {}^k\mathbf{T}_0 \quad (2)$$

where ${}^k\mathbf{T}_0$ is a 6×6 matrix to transform the components of the stiffness matrix ${}^k\mathbf{C}$ of the k -th flexure from the local frame S_k to a ground frame S_0 . In particular, the expression of ${}^k\mathbf{T}_0$ is:

$${}^k\mathbf{T}_0 = \left[\begin{array}{c|c} {}^k\mathbf{R}_0 & \mathbf{0} \\ \hline {}^k\tilde{\mathbf{r}}_0 \cdot {}^k\mathbf{R}_0 & {}^k\mathbf{R}_0 \end{array} \right] = \left[\begin{array}{c|c} {}^0\mathbf{R}_k^T & \mathbf{0} \\ \hline ({}^0\tilde{\mathbf{r}}_k \cdot {}^0\mathbf{R}_k)^T & {}^0\mathbf{R}_k^T \end{array} \right] \quad (3)$$

where ${}^k\mathbf{R}_0$ denotes the rotation matrix of frame S_0 with respect to frame S_k and ${}^0\tilde{\mathbf{r}}_k$ indicating the skew symmetric matrix of the position vector ${}^k\mathbf{r}_0$, which locates the origin of frame S_0 with respect to frame S_k .

For the compliant spherical 3R chain shown in Fig. 3, made by three identical spherical flexures with coincident centers O_k and mutually orthogonal axes, the overall compliance matrix expressed with respect to the reference frame of the first spherical flexure (namely, $S_0 \equiv S_1$) results as [24]:

$${}^0\mathbf{C}^{3R} = \left[\begin{array}{cccccc} C_{x,f_x} & 0 & 0 & 0 & C_{x,m_y} & C_{x,m_z} \\ 0 & C_{y,f_y} & 0 & C_{y,m_x} & 0 & C_{y,m_z} \\ 0 & 0 & C_{z,f_z} & C_{z,m_x} & C_{z,m_y} & 0 \\ 0 & C_{\theta_x,f_y} & C_{\theta_x,f_z} & C_{\theta_x,m_x} & 0 & 0 \\ C_{\theta_y,f_x} & 0 & C_{\theta_y,f_z} & 0 & C_{\theta_y,m_y} & 0 \\ C_{\theta_z,f_x} & C_{\theta_z,f_y} & 0 & 0 & 0 & C_{\theta_z,m_z} \end{array} \right]_{3R} \quad (4)$$

where:

$$\begin{aligned} C_{x,f_x} &= C_{y,f_y} = C_{z,f_z} = \frac{R\theta (I_n GJ + GJ R^2 A + R^2 E A I_n)}{E A I_n GJ} = C_t \\ C_{\theta_x,m_x} &= C_{\theta_y,m_y} = C_{\theta_z,m_z} = \frac{R\theta (I_n E I_m + I_n GJ + GJ I_m)}{GJ E I_m I_n} = C_r \\ C_{x,m_y} &= C_{y,m_z} = C_{z,m_x} = C_{\theta_x,f_z} = C_{\theta_y,f_x} = C_{\theta_z,f_y} = \frac{-2R^2 \sin(\theta/2)}{GJ} = C_{tr1} \\ C_{x,m_z} &= C_{y,m_x} = C_{z,m_y} = C_{\theta_x,f_y} = C_{\theta_y,f_z} = C_{\theta_z,f_x} = \frac{2R^2 \sin(\theta/2)}{E I_n} = C_{tr2} \end{aligned} \quad (5)$$

In Eq. 5, E and G are the Young's and shear moduli of the employed material. A , R , I_m , I_n and J are, respectively, cross section area, centroidal axis radius, area moments of inertia and torsional constant of the flexure cross section (refer to Fig. 2) that read as follows [25]:

$$A = \frac{r_o^2 \beta}{2} - \frac{r_i^2 \beta}{2} = \frac{(r_o^2 - r_i^2) \beta}{2} \quad (6)$$

$$R = \frac{4 (r_o^3 - r_i^3) \sin \beta / 2}{3 (r_o^2 - r_i^2) \beta} \quad (7)$$

$$I_m = \frac{1}{8} (r_o^4 - r_i^4) (\beta - \sin \beta) \quad (8)$$

$$I_n = \frac{1}{8} (r_o^4 - r_i^4) (\beta + \sin \beta) - \frac{8 (r_o^3 - r_i^3)^2 \sin^2 (\beta / 2)}{9 (r_o^2 - r_i^2) \beta} \quad (9)$$

$$J = \frac{2}{3} \sin^3 (\beta / 2) (r_o^4 - r_i^4) - 16 \sin^4 (\beta / 2) (V_L r_o^4 + V_S r_i^4) \quad (10)$$

where:

$$V_L = 0.10504 - 0.2 \sin (\beta / 2) + 0.3392 \sin^2 (\beta / 2) - 0.53968 \sin^3 (\beta / 2) + 0.82448 \sin^4 (\beta / 2)$$

$$V_S = 0.10504 + 0.2 \sin (\beta / 2) + 0.3392 \sin^2 (\beta / 2) + 0.53968 \sin^3 (\beta / 2) + 0.82448 \sin^4 (\beta / 2)$$

Equation 10 is the formula for the torsional constant firstly proposed by J.B. Reynolds to account for the warping of annulus sector cross-sections [15, 16].

As one can notice from Eqs. 4 and 5, the compliance matrix of the compliant spherical 3R chain with respect to frame S_0 still retains diagonal translational and rotational sub-matrices (${}^0\mathbf{C}_{uf}$ and ${}^0\mathbf{C}_{\theta m}$), and is only a function of four independent factors: C_t , C_r , C_{tr_1} and C_{tr_2} . C_r is the primary rotational compliance of the 3R chain, which should be as high as possible to minimize resistance to desired spherical motions. C_t is a secondary translational compliance, which should be as close as possible to zero to minimize drift of the desired center of spherical motion (O_0) under the action of the force vector ${}^0\mathbf{f}$ applied on the end-link. C_{tr_1} and C_{tr_2} are secondary coupled rotational-translational compliances, which should be as close as possible to zero to minimize spherical motion center drift under the action of the torque vector ${}^0\mathbf{m}$ applied on the end-link.

3 Parametric Evaluation of the Compliant Spherical 3R Chain

This section investigates the influence of flexure geometry on the ability of the considered 3R chain in the generation of spherical motions. The study is performed by evaluating the following three indices:

Fig. 4 The influence of varying w^* and w^*/β on f_1

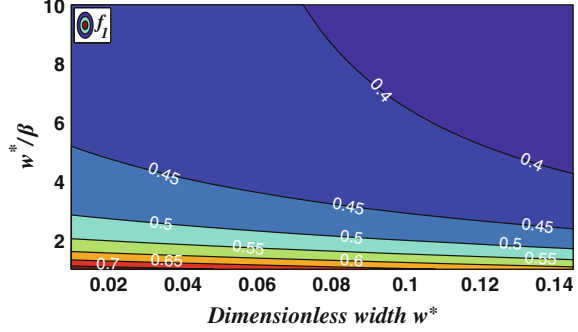
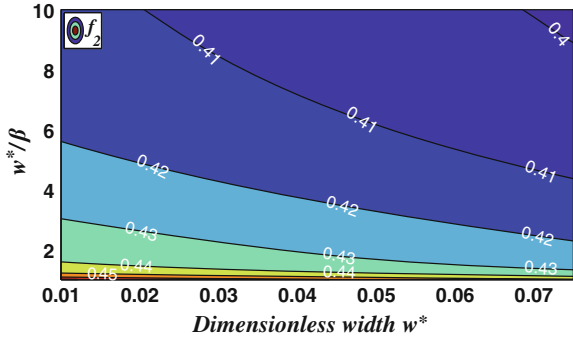


Fig. 5 The influence of varying w^* and w^*/β on f_2 for $\theta = 45^\circ$



$$f_1 = \left| \frac{1}{r_o^2} \frac{C_t}{C_r} \right| \quad f_2 = \left| \frac{1}{r_o} \frac{C_{tr1}}{C_r} \right| \quad f_3 = \left| \frac{1}{r_o} \frac{C_{tr2}}{C_r} \right| \quad (11)$$

that represent the dimensionless ratios of the translational and coupled translational-rotational compliances of a generic compliant spherical 3R chain to the rotational counterpart. In the definition of these indices, the curvature radius r_o of the SF is used as characteristic size to obtain scale-independent expressions that only depend on the flexure shape dimensionless parameters w^* , β and θ . In particular, f_1 is only a function of w^* and w^*/β , whereas f_2 and f_3 also depend on θ . Among the possible choices, r_o has been chosen as characteristic length since it describes the overall encumbrance of the 3R chain, which is often the most important application constraint in the design optimization process. Plots of Eq. 11 are reported in Figs. 4, 5, 6, 7 and 8 as a function of the SF aspect ratios w^* and w^*/β . The dependency of f_2 and f_3 on θ is shown by comparing Figs. 5 and 7 (for $\theta = 45^\circ$) to Figs. 6 and 8 (for $\theta = 90^\circ$). In addition, the contour plot of the size independent factor $C_r^* = C_r * r_o^3 / \theta$ (which is constant irrespective of the value of θ and only dependent on the cross section aspect ratios w^* and w^*/β) is reported in Fig. 9. As figures show, maximization of

Fig. 6 The influence of varying w^* and w^*/β on f_2 for $\theta = 90^\circ$

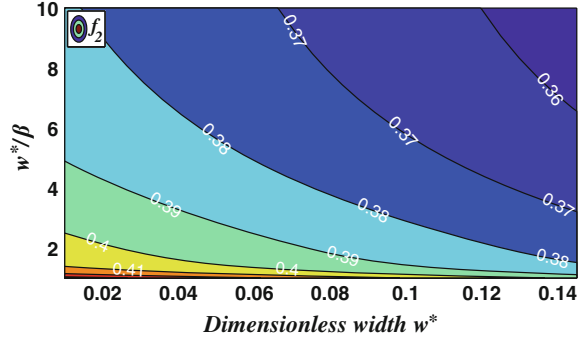


Fig. 7 The influence of varying w^* and w^*/β on f_3 for $\theta = 45^\circ$

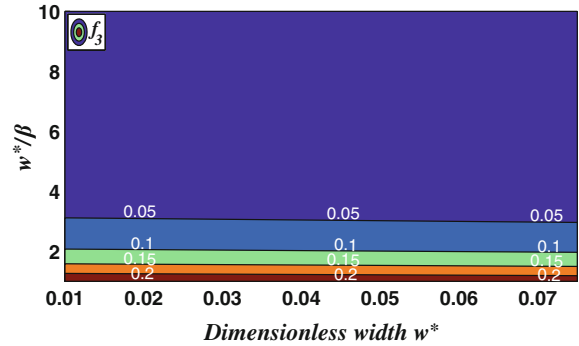
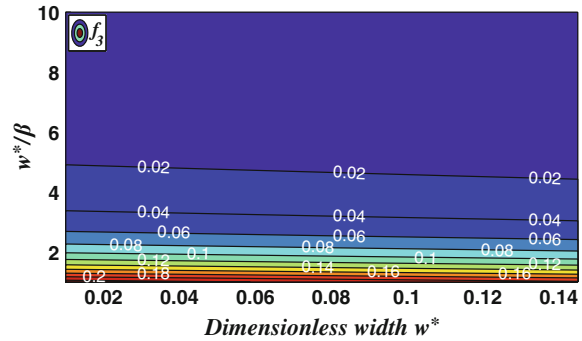
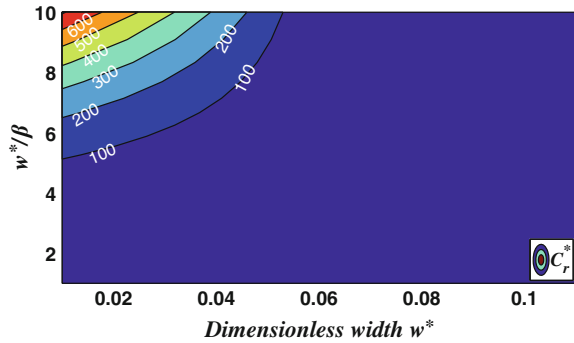


Fig. 8 The influence of varying w^* and w^*/β on f_3 for $\theta = 90^\circ$



the spherical motion generation capabilities of the considered compliant 3R chain (that is, minimization of secondary to primary compliance ratios) can be obtained by adopting the largest possible values for θ and w^*/β (within the limits of physical realizability) as well as for w^* (within the limit of validity of the slender beam approximation; namely $w^* < 0.1\theta$).

Fig. 9 The influence of varying w^* and w^*/β on C_r^*



4 Conclusions

A compliant open chain featuring three in-series connected identical primitive spherical flexures with coincident centers of curvature and mutually orthogonal axes of principal compliance, is introduced and analyzed for application in spherical compliant mechanisms. First, the closed form compliance equations of the proposed spherical chain are presented as a function of flexure dimensions and employed material. The obtained equations are then used to study the influence of flexure dimensions on spherical chain parasitic motions. The study is performed by evaluating three dimensionless ratios of the translational and coupled translational-rotational compliances of a generic compliant spherical 3R chain to the rotational counterpart. The results show that maximization of the spherical motion generation capabilities of the considered compliant 3R chain (that is, minimization of secondary to primary compliance ratios) can be obtained by adopting the largest feasible values for θ and w^*/β (within the limits of physical realizability) as well as for w^* (within the limit of validity of the slender beam approximation; namely $w^* < 0.1\theta$). Future activities will be devoted to the study of the compliant spherical chains in the case of stockier flexures as well as in the large deformation range.

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