Monolithic and Statically Balanced Rotational Power Transmission Coupling for Parallel Axes

D. Farhadi Machekposhti, N. Tolou and J.L. Herder

Abstract A new fully compliant rotational power transmission mechanism is presented. The design is based on the Pseudo-Rigid-Body Model (PRBM) of the Oldham constant velocity coupling. It can be fabricated as a single piece device with planar materials which make it suitable for micro scale applications. The internal stiffness of the proposed structure is eliminated by static balancing technique. Therefore, the compliance and zero stiffness behavior compensate for the structural error and poor efficiency inherent in rigid-body Oldham coupling, resulting in high mechanical efficiency power transmission system. The device is designed and its motion, torsional stiffness, and torque-angular displacement relations are predicted by the PRBM and finite element modeling. A large/macro scale prototype was manufactured and measured to evaluate the concept. This high efficient power transmission system can be applied in different applications in precision engineering and the relevant field such as micro power transmission system.

Keywords Compliant mechanism · Static balancing · Power transmission · Coupling · MEMS

1 Introduction

In many cases such as microtransmissions and microengines, a constant velocity power transmission system is required to transfer the rotational motion from one rotational axis to another rotational axis with a parallel offset (Sniegowski et al.

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1996; Garcia et al. 1995). In the field of precision engineering, this problem was simply solved by using a couple of gears with the same number of tooth. However, this solution has a poor mechanical efficiency due to the gearing contact. Moreover, a precise micro assembling process is required to have a proper gearing system (Miller et al. 1996).

In prior art, different types of constant velocity couplings have been offered as a solution to accommodate with alignment errors for power transmission lines. However, they are rigid-body linkages, and like gearing systems, they have many disadvantages such as friction, backlash, wear, need for assembly, lubrication, and maintenance.

Compliant mechanisms have shown a great deal of potential in providing better solutions for transmission mechanisms (Farhadi Machekposhti et al. 2015a). These mechanisms drive their motion from elastic deformation of flexible segments rather than using conventional kinematic pairs (Howell 2001). This articulation became popular in the field of precision engineering due to the elimination of rigid-body kinematic joints which also eliminates the effect of backlash, wear, friction, and need for lubrication and assembly. A compliant coupling for all different and small alignment errors, angular and translational misalignment, was presented based on rigid-body Oldham coupling (Goodknight 1999; Soemers 2011). Wire flexures were used in those designs in order to provide an extra degrees of freedom for angular misalignment as well as translational misalignment between input and output axes. However, this cannot grantee a constant velocity transmission between input and output shafts due to the asymmetric configuration in respect to the homokinetic plane (Hunt 1973). Besides, they can only be applicable for low torque transmission due to the low torsional stiffness of their compliant design. Moreover, the design has a poor mechanical efficiency due to the overall compliancy of the designed structure.

Traditional kinematic pairs offer near zero stiffness around a desired axis and large stiffness along the other axes. However, the monolithic nature of compliant systems gives rise to a drawback: the elastic deformation of the monolithic structure requires significant force and energy which is considered a ‘necessary evil’ in compliant mechanism designs. In other words, the mechanical efficiency is poor, and it takes continuous force to hold the mechanism in position (Herder et al. 2000). This fact potentially results in problems such as rotation transmission with non-constant torque, overheating of the actuators, high energy consumption, insufficient travel range, low speed, and the need for larger actuators. However, the deformation energy is not lost; it is stored. It is a conservative force, and therefore it can be statically balanced (Herder et al. 2000; Tolou et al. 2010). As a consequence, these systems can be operated with much less effort as compared to the unbalanced situation.

The purpose of this work is to design a statically balanced and compliant constant velocity power transmission coupling which can efficiently transfer the rotational motion between two parallel axes.

The design of the mechanism is discussed in the following section. The conceptual design is demonstrated and the theoretical model, Pseudo rigid-body model and static balancing conditions, are studied. The model is then verified with experimental results and Finite Element Modeling (FEM).

2 Theoretical Model

The proposed compliant power transmission coupling is designed by applying conventional kinematic synthesis and using a Pseudo-Rigid-Body Model (PRBM) to create an equivalent compliant design. Besides, Static balancing technique is considered to provide static balancing conditions for the proposed design in order to have a high efficiency power transmission system.

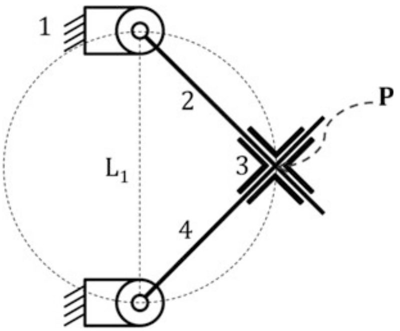
The next sections describe the design in terms of rigid-body kinematic and then the PRBM is used to study the torque-angular displacement relation and static balancing conditions.

2.1 Rigid-Body Oldham Coupling

The rigid-body Oldham coupling is a specific type of four-bar linkage (Freudenstein et al. 1984). It has three movable parts, one coupled to the input shaft, one coupled to the output shaft, and a middle component which is connected to the first two parts by prismatic joints. These two sliders, prismatic joints, are two frictional joints which lose lot of energy during the motion. The direction of the prismatic joint on one side is perpendicular to the direction of another prismatic joint on the other side. The schematic of the mechanism is shown in Fig. 1.

It has two fixed and fully rotating frame joints which act as bearings for two parallel axes, crank 2 and 4. If the input link, 2, rotates through some angle, then the coupler link, 3, rotates through the same angle. This in turn rotates the output shaft, 4, through the same angle. Therefore, the two links, 2 and 4, rotate together and the

Fig. 1 Rigid-body Oldham coupling



velocity ratio remains constant at 1:1 throughout the rotation. Link 1 is ground link with length L_1 which actually is the offset between input link 2 and output link 4. The direction of two prismatic joints intersect each other at point P, the center of the coupler link. For a full cycle motion of the input link, the point P moves along a circular path with the diameter L_1. Therefore, the range of motion in each prismatic joint in each cycle is exactly the distance between the two parallel axes or the offset.

2.2 Pseudo Rigid-Body Model and Static Balancing Conditions

The pseudo-rigid-body model is used to convert the rigid-body Oldham coupling into a compliant design. This is done by rigid-body replacement synthesis (Howell 2001). The full cycle revolute joints of the input and output axes remain as a conventional rigid-body revolute joints since the mechanism will be connected to the input and output shafts, Fig. 2. The two prismatic joint can be replaced by translational compliant suspensions. Therefore, two translational springs K_1, and K_2 are considered as a replacement of the compliant translational suspension to simplify the analysis based on the pseudo-rigid-body model.

The input torque required to deal with stiffness of the system can be found by means of the virtual work principle. The analysis is based on static equilibrium and the energy equation can be written as

$$T_2 \delta\theta_2 - \delta V_e = 0. \tag{1}$$

where, T_2 and θ_2 are the input torque and angle of input shaft, respectively. V_e is the elastic potential energy which can be given by

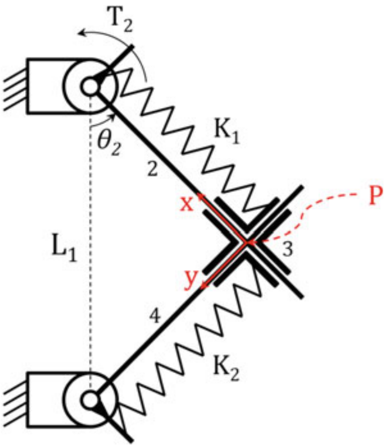


Fig. 2 The Pseudo-rigid-body model for an Oldham coupling

$$V_e = \frac{1}{2}\left(K_1x^2 + K_2y^2\right) \tag{2}$$

The mechanism can be statically balanced, the required input T_2 can be equal to zero, if the total elastic potential energy of the mechanism be a constant value over different input angle. This can be achieved by two constant and zero length springs K_1 and K_2 which have equal stiffness and they are in rest position at point P, input and output axes are collinear when the springs are in rest position. Therefore, these conditions can simplify the total elastic potential energy of the system as

$$V_e = \frac{1}{2}K_1\left(x^2 + y^2\right) = \frac{1}{2}K_1L_1^2 = const. \tag{3}$$

Therefore, the mechanism should be designed such that the parallel offset of the two rotational axes provides the preloading to compensate the internal stiffness of the mechanism.

2.3 Compliant Design

The compliant counterpart of the monolithic and statically balanced power rotational transmission coupling for parallel axes is illustrated in Fig. 3.

The design comprises two translational compliant suspensions which are sharing the main frame. The main shuttles are decoupled and connected to the input and output axes.

The desired range of motion, high off-axis stiffness, and compact size are considered as design criteria to select the desired compliant translational suspension among the several different types of the compliant translational joints which were found and studied in prior art (Farhadi Machekposhti et al. 2012, 2015b).

3 Model Validation

This section describes prototyping, static torque, and actuation torque measurements, the measurement protocols and the results obtained from the measurements and finite element modeling.

3.1 Fabrication

A prototype with flexures out of stainless steel AISI316L was made for the experimental evaluation, Fig. 4. The set of parameters that defined the compliant structure are presented in Table 1.

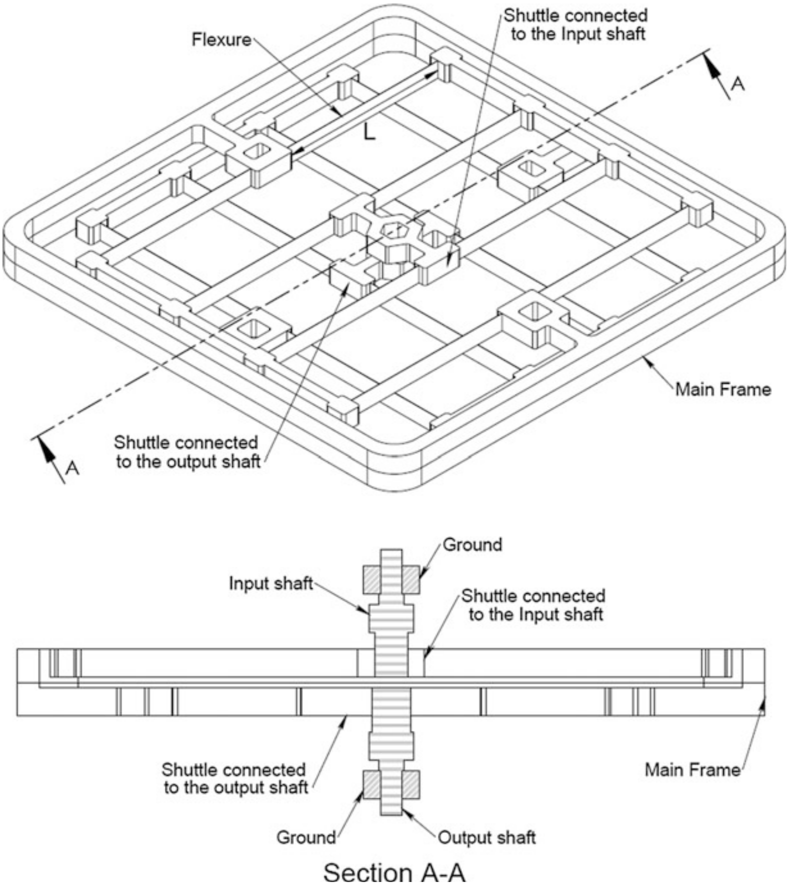


Fig. 3 Compliant counterpart of the monolithic and statically balanced power rotational transmission coupling

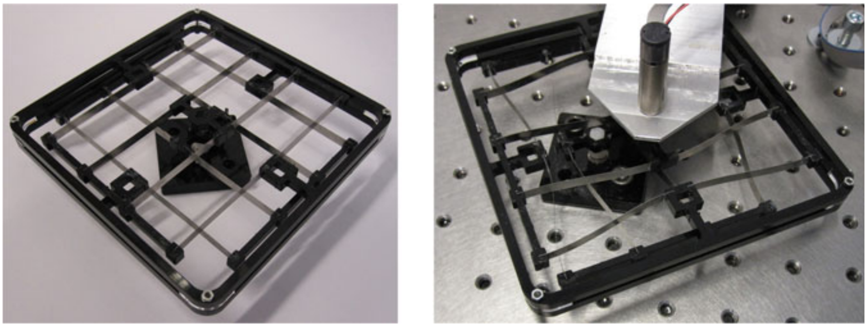


Fig. 4 The prototype of the compliant and statically balanced power rotational transmission coupling in initial and deflected positions

Table 1 Set of parameters of the flexures for the statically balanced compliant power rotational transmission coupling

Parameters	Values (mm)
Flexure length	50
Flexure thickness	0.2
Flexure out of plane thickness	5

The prototype is designed and fabricated for the maximum offset. This was limited by the yield strength of austenitic stainless steel AISI316L rated at 500 MPa.

3.2 Experimental Evaluation

An experimental setup was designed and built in order to measure both the torsional stiffness and minimum actuation torque of the designed statically balanced compliant power transmission coupling, Fig. 5.

The input axis is connected to the drive shaft. In order to find the torsional stiffness through static torque measurement, the output shaft is directly connected to

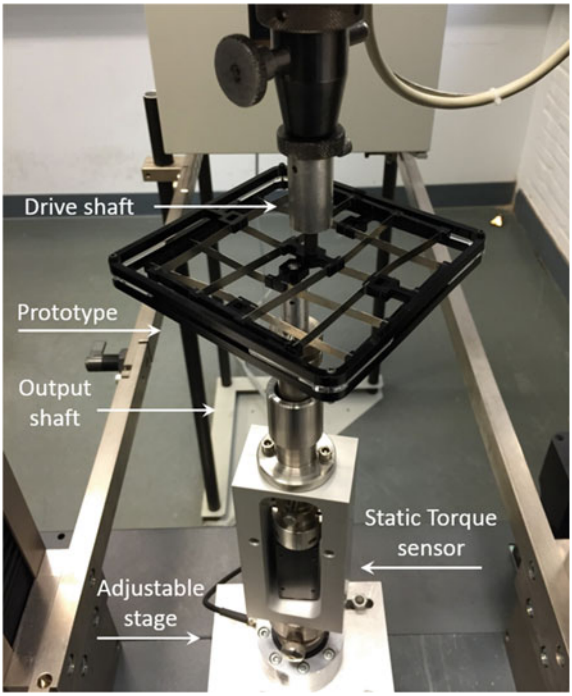


Fig. 5 Experimental setup for torsional stiffness and minimum actuation torque measurements on compliant and statically balanced power rotational transmission coupling. In this figure the setup is adjusted for 10 mm offset

the static torque sensor, HBM T20WN, which was mounted on an adjustable stage for different offset between input and output shafts. The input shaft was actuated for failure of the structure, and the reaction torque at the output shaft was measured by a static torque sensor which was linked to the angular displacement of the input shaft.

The torque-angular displacement characteristic, torsional stiffness, of the proposed compliant rotational power transmission coupling for different offset for both static torque experiment and finite element modeling are shown in Fig. 6. This shows the torque capacity of the designed compliant power transmission coupling. As can be seen, by increasing the offset between two axes the torsional stiffness will decrease and as result the maximum torque capacity of the proposed power transmission coupling will decrease as well.

Approximately 4 % error is observed between experimental result and finite element modeling. However, this can be explained by inaccuracy of the adjustable stage and the flexibility of the intermediate stages.

In order to find the minimum actuation torque, the output shaft is disconnected from the static torque sensor and it is free to rotate, quasi static torque measurement. The results for the minimum actuation torque of the proposed power transmission system for one full cycle rotation are shown in Fig. 7.

As can be seen, the experimental result and finite element modeling shows the proposed compliant rotational power transmission coupling is nearly statically balanced as this feature was also predicted by pseudo-rigid-body model. Therefore, The torsional stiffness of the proposed compliant power rotational transmission coupling can be increased without increasing the actuation torque. This can be increased by different approaches such as design for exact constraint folded flexures using slave flexures, change the compliant design configuration and beam combinations, increasing the dimensions, etc.

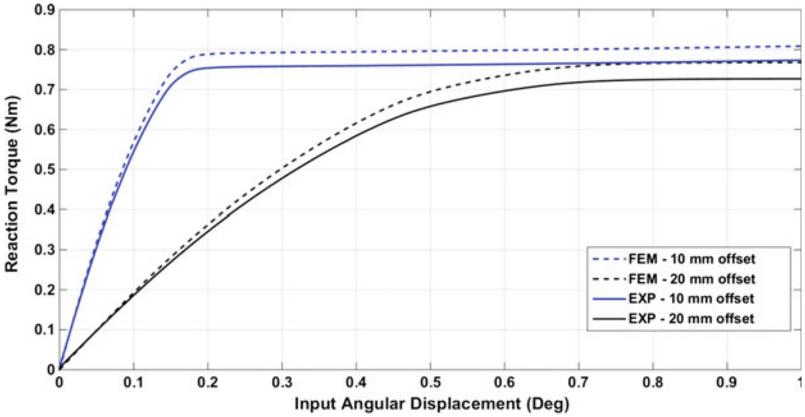


Fig. 6 Torque-angular displacement relation, torsional stiffness, for the compliant and statically balanced power rotational transmission coupling, for experiment (*solid line*) and finite element modeling (*dash line*) in two different parallel offsets

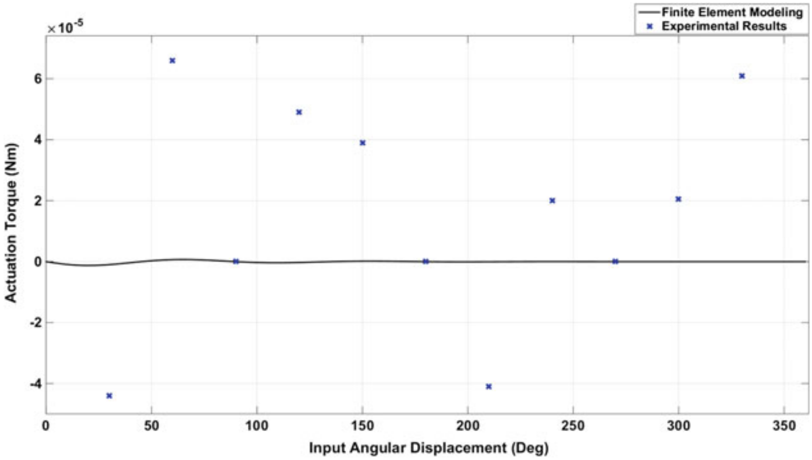


Fig. 7 The experimental results and finite element modeling of the minimum actuation torque of the compliant and statically balanced power rotational transmission coupling for 20 mm parallel offset between input and output axes

4 Conclusions

A new fully compliant and statically balanced rotational power transmission coupling is presented and its principle is described. The design is from the PRBM of the rigid-body Oldham coupling. The planar nature of the design makes it suitable for a manufacturing process on both macro and micro scales. The internal positive stiffness of the proposed compliant system is cancelled out by static balancing technique in order to have a power transmission coupling with high mechanical efficiency. This feature makes the design capable to be used for high torque applications. Prototypes were manufactured and evaluated by experimental data and finite element modeling. Results support the design and the theoretical analysis, PRBM. Moreover, It was shown, this compliant power transmission system has a great potential for high torque applications on both macro and micro scales.

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