Swiss watch featuring Dutch precision

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SWISS WATCH FEATURING DUTCH PRECISION

A method is introduced to design compliant micro transmission mechanisms which double the motion frequency of a cyclic input motion. Compliant embodiments are generated based on exploiting the singularity in a double-slider mechanism, which provides building blocks with a frequency-multiplication factor of two. It is shown that the proposed building blocks can be concatenated for higher frequency-multiplication ratios. To validate the building block approach, a compliant micro transmission mechanism is presented which quadruples the frequency of a cyclic rectilinear input motion.

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Introduction

Displacement, force, and operation frequency are the main criteria for selecting an actuator for an application, while also size, cost, efficiency, and power supply have a great impact on the final choice. In many cases, actuator specifications do not match the requirements of a given application. In such cases a power transmission mechanism may be needed.

For instance, among different micro-actuators, thermal micro-actuators can offer high forces and displacements. However, they are limited to low operating frequencies as compared to other actuation schemes [1]. These actuators can be applied for more applications if a micro power transmission can be integrated to transform the low frequency of the input motion into an output motion with higher frequency.

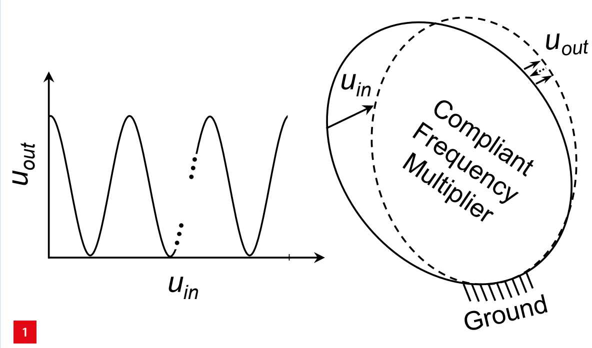
Gear trains are the only examples of transmission mechanisms that have been used in mechanical and micro-electromechanical systems (MEMS) to multiply the motion frequency. However, gears are rigid-body mechanisms which generally give rise to many drawbacks, including friction, backlash, wear, and the need for assembly, lubrication, and maintenance. Besides, it is difficult to achieve a continuous rotational bearing with the existing MEMS fabrication technology.

Recently, compliant mechanisms became popular in the field of micro transmission mechanisms. Compliant transmission couplings [2] [3], micro motion converters [4], and compliant stroke multipliers are some of the few examples of compliant transmission mechanisms that exist in literature. Compliant mechanisms transmit and transform force and motion by undergoing elastic deformation of their flexible segments as opposed to rigid-body motions of traditional linkages. The monolithic nature of these mechanisms allows for miniaturisation. Therefore, this enables a compact system design by integration of the power transmission and actuation part. However, finite travel range of the rotational flexures is the main kinematic limitation in this type of mechanisms.

Here, we report a new method for the design of compliant frequency-multiplier transmissions, utilising a building block approach based on exploiting the singularity of the double-slider mechanism. The main advantage of this proposed movement is that the mechanism does not need full-cycle rotational joints or frictional contacts.

Method

A limited-cycle kinematic is proposed to increase the motion frequency within a finite travel range. This will eliminate the need for problematic continuous, infinite-travel-range, rotational joints or rigid contacts for frequency multiplication at micro-scale. A generalised input-output kinematic relationship for such a transmission mechanism is shown in Figure 1.



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The generalised input-output displacement relationship of a compliant frequency multiplier.

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To increase the motion frequency, the direction of the output motion, u_{out}, needs to reverse while the input is subjected to the displacement u_{in}. This can be shown in the first kind of singularity in the rigid-body mechanisms. This type of kinematic singularity refers to a configuration where a kinematic chain reaches the boundary of the workspace. The input-output frequency-multiplication ratio can be identified based on the number of singularities of the first kind, m, in the kinematic chain within the considered range of motion, and can be given by:

$$f_{out} / f_{in} = m + 1 \tag{1}$$

Here f_{out} (in cycles per second, Hz) and f_{in} are the motion frequency of the output and the input members of the mechanism, respectively.

The proposed building block in this article is based on a four-bar linkage, where for a finite travel range there is only one configuration representing a singularity of the first kind. This can be shown in the double-slider four-bar mechanism (Figure 2a), which can be a favourable choice for MEMS devices due to the rectilinear input and output motions. Therefore, based on Equation 1, the mechanism can multiply the input motion frequency with a ratio of 2 (Figure 2b). As can be seen, the motion of the output slider u_{out} completes a full cycle while the input slider displaces with u_{in} from left to right, which is half a complete cycle.

Theoretically, a frequency-multiplier mechanism with the ratio of 2^n can be achieved by concatenating n number of frequency-doubler mechanisms, where $n = 1, 2, ..., N$. However, the output performs a small displacement compared to the input since the mechanism is working around the singularity. Therefore, this limits the use of this mechanism in a serial combination to reach higher multiplication ratios or a desired output displacement.

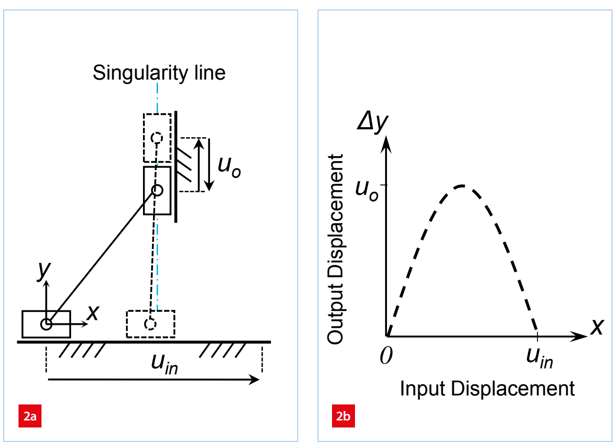
Two partial compliant frequency-doubler building blocks are proposed, shown in Figure 3. The stroke of the output is amplified by arranging two compliant equivalents of the double-slider mechanism in series with a shared input. The building block shown in Figure 3 can double the output frequency when a rectilinear cyclic motion with sinus or cosine function is subjected to the input, respectively.

The output displacement of the proposed frequency-doubler building blocks is limited by the maximum input displacement and the length of the beams. However, a compliant mechanical stroke amplifier can be paired with the output of the mechanism to amplify the displacement with a desired factor. Two different examples are presented herein, which illustrate the combination of the proposed compliant cycle doubler building blocks with different types of stroke amplifier concepts (Figure 4).

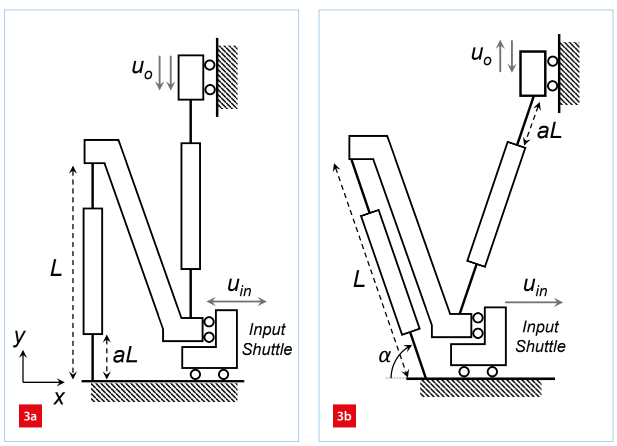
The output displacement from the cycle doubler building blocks, u_o^1, can be amplified to a desired output displacement, u_{out}, by a stroke amplifier. Case I comprises two sets of angled beams where their ends are constrained by a vertical beam, shown in Figure 4a. The first set, with the angle of α_1, is the cycle doubler mechanism, equivalent with the angled arrangement shown in Figure 4b. The second set, with the angle of α_2, acts as a stroke amplifier with the instant multiplication ratio of tan α_2, where the condition $\alpha_2 < 45°$ should be satisfied to get a stroke multiplication ratio higher than one. Case II, illustrated in Figure 4b, includes a compliant cycle doubler building block, equivalent with the arrangement shown in Figure 4a, paired with a lever arm as a stroke amplifier with an multiplication ratio of b_2 / b_1.

Design

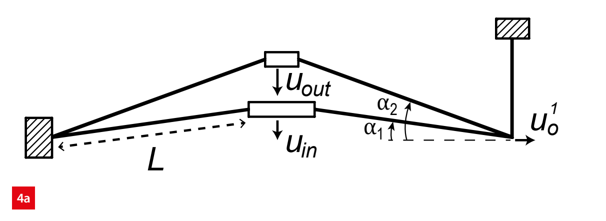
A compliant frequency-quadrupler transmission mechanism has been designed based on the proposed

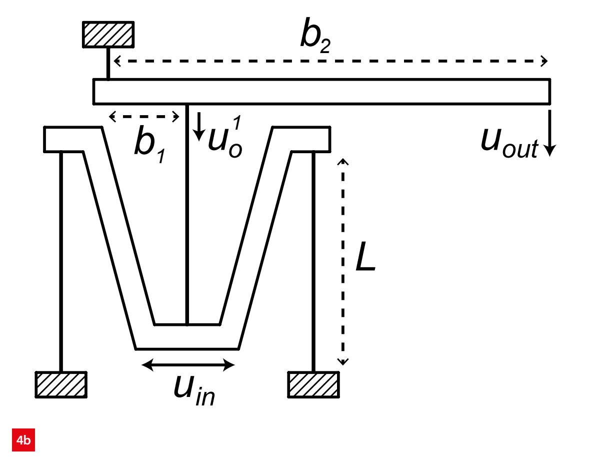


The double-slider four-bar mechanism.
(a) Rigid-body mechanism representation.
(b) The input-output displacement relationship.



Partially compliant frequency-doubler building blocks, with two different initial shapes.
(a) At the singularity.
(b) At the angled arrangement.

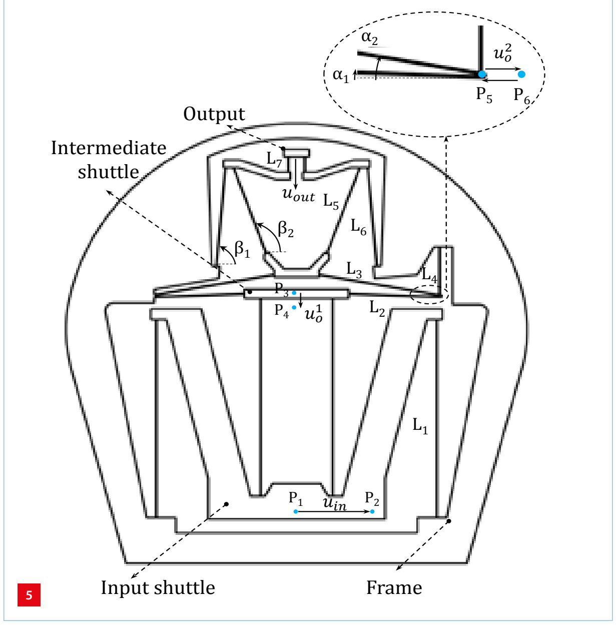




Combinations of frequency-doubler building block and different compliant stroke amplifier concepts.
(a) Double-slider mechanism (Case I).
(b) Lever mechanism (Case II).

method, shown in Figure 5. The set of design parameters are summarised in Table 1.

Furthermore, a constant thickness of t = 30 µm is considered in the drawing for all the flexures included in the design. The design is composed of two frequency-doubler building blocks, concatenated with a set of stroke amplifiers. The design comprises an input shuttle which can be subjected to a reciprocating input motion, and it is



The design embodiment of a compliant micro frequency-quadrupler.

connected to the ground and an intermediate shuttle each with two parallel long-length flexures. This is a fully compliant equivalent of the building block shown in Figure 4a. For an input displacement of u_{in} towards the right (from point P_1 to point P_2), the intermediate shuttle moves downwards from point P_3 to point P_4.

Table 1
Design parameters for the micro frequency-quadrupler transmission mechanism.

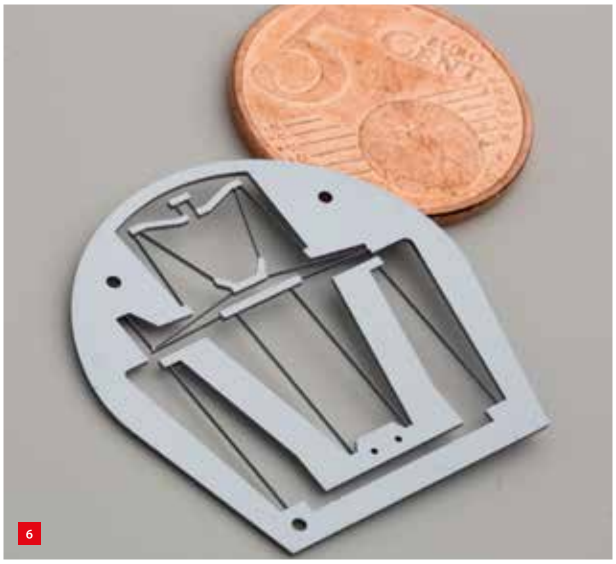
Parameter	Value
L_1	13 mm
L_2	5.5 mm
L_3	7.5 mm
L_4	3 mm
L_5	6 mm
L_6	6.5 mm
L_7	1 mm
β_1	85°
β_2	110°
α_1	2.2°
α_2	10°

Besides, the intermediate shuttle follows similar movement when the input moves towards the left with a displacement of u_{in}. Therefore, the intermediate shuttle completes two cycles for a full cyclic movement of the input, which results in a frequency-multiplication factor of two. The intermediate shuttle is connected to the ground and a cantilever beam, equivalent to the concept of Figure 4a (Case I), via two angled long-length flexures, with the angle α_1. The endpoint P_5 travels to point P_6 and then returns back to the same point P_5 (a complete cycle), while the intermediate shuttle moves from P_3 to point P_4.

This provides another frequency-duplication effect, which results in an overall frequency-multiplication ratio of four between the input movement and the motion at point P_6. However, the stroke is small due to a consecutive combination of two motion frequency multipliers. Therefore, a stroke amplifier is connected to the output of the compliant frequency-quadrupler mechanism with a multiplication ratio of 1:19.

Fabrication and characterisation

A micro-device was fabricated in silicon using deep reactive ion etching (DRIE), shown in Figure 6.
The design was first patterned on a w = 525 µm thickness silicon wafer and then etched by DRIE. This was done with the basic Bosch plasma etching process, which includes



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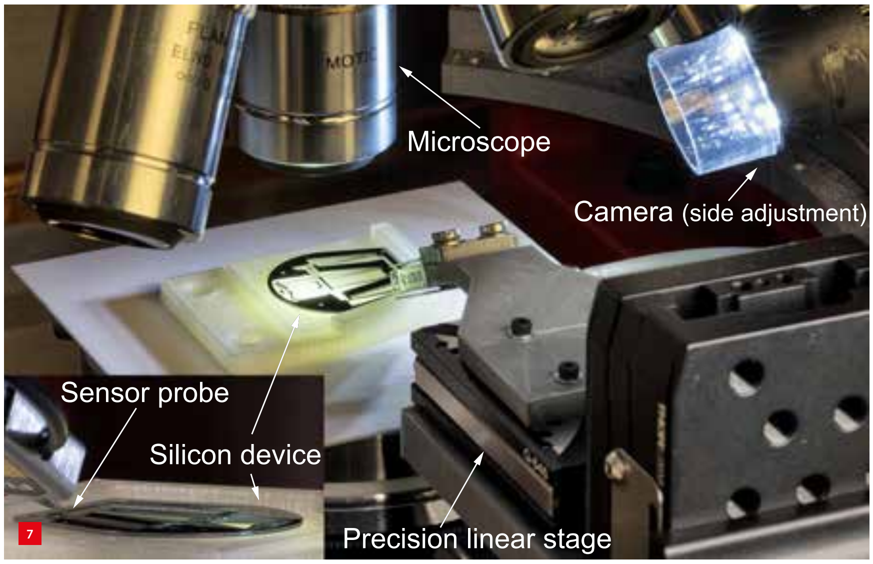
The prototype of the compliant frequency-quadrupler fabricated out of silicon using the DRIE process.



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Experimental set-up to evaluate the actuation force, and the input-output kinematics of the compliant frequency-quadrupler.

two subprocesses: the etching and the passivation, to produce a device with a high aspect ratio.

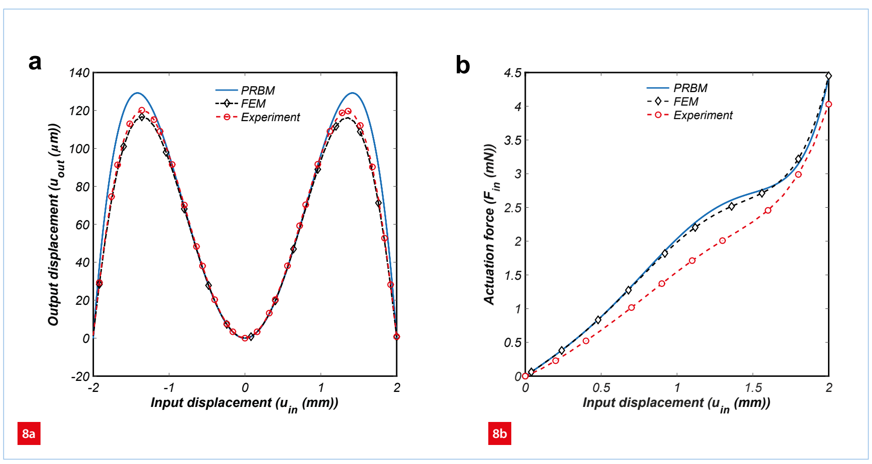
A customised test set-up was constructed for testing the actuation stiffness and the input-output kinematics of the silicon device, shown in Figure 7. The force deflection of the device was measured using a 20-gram force sensor (FUTEK LSB200) with a resolution of 20 μN. The force sensor was mounted on a precision linear stage (PI Q-545), with a resolution of 1 nm and minimum incremental motion of 6 nm, to provide a rectilinear input motion. A displacement of 2 nm was applied to the input shuttle of the micro-device, and the movement of the output shuttle was simultaneously captured by an optical microscope (Keyence VHX-1000E). The displacement was analysed afterwards using image processing, where it was detected with 500-nm accuracy.

Performance

The optical displacement measurement, the finite-element model (FEM) and the pseudo-rigid-body model (PRBM) show the same behaviour and order of magnitude for the input-output kinematic relationship, shown in Figure 8a. As can be seen, the proposed compliant transmission mechanism multiplies the input motion frequency with a factor of four, and with a maximum output displacement of 120 μm. The PRBM shows a maximum of 6.7% discrepancy with the experimental results. This can be explained by the elastokinematic effects since the presented theoretical plot is based on the PRBM.

The force-deflection measurement is illustrated and compared to the FEM and the PRBM in Figure 8b. The results show a nonlinear correlation between the actuation force and the displacement, which can be explained by the nonlinear kinematics of the proposed compliant frequency-doubler building block. Clearly, by increasing the input displacement the compliant device is behaving as a linear spring, softening spring, and hardening spring, sequentially. Besides, it is shown that the results from the FEM and the PRBM are in agreement. The small discrepancy between these results, maximum 3.4%, illustrates the accuracy of the PRBM.

As can be seen in Figure 8b, the result from the measurement shows a more linear stiffness behaviour as compared to both the FEM and the PRBM. Besides, a 9,4% discrepancy is observed at maximum actuation force between the measurement and the PRBM. This can be explained by uncertainties in the thickness measurement by SEM, ±1.5 μm. A decrease in thickness t of 0,5 μm for flexible members with an initial average thickness of 21.25 μm results in a 7.8% decrease of the actuation force. Moreover, the difference in nonlinear stiffness behaviour, between the PRBM and the experiment, can be explained



8a 8b

The results for the micro compliant frequency-quadrupler from the theoretical model (pseudo-rigid-body model, PRBM), finite-element model (FEM) and experiment.
(a) The input-output kinematics.
(b) Force-displacement characteristics.

by the stiffness of the compliant stroke amplifier, K_{SA}, in which a similar trend can be observed between the PRBM and the experiment, i.e. a 25% decrease in the actuation stiffness of the compliant stroke amplifier with an initial stiffness of K_{SA} = 8.8 N/mm.

As can be seen, based on the force-deflection results, there is a trade-off between adding compliant multipliers (frequency or stroke) and the additional motion stiffness that is associated with those. However, the principle of static balancing can be applied in each building block separately since the elastic force is a conservative force. For instance, a balancing segment (preloaded beams) which provides a negative stiffness can be added to cancel the positive stiffness of each compliant building block.

Future developments will focus on actuation force reduction using static balancing with preloaded beams. Moreover, it will also include the integration of an embedded actuator to study the kinematics of the proposed compliant micro-transmission in high-speed operation.

Conclusions

A monolithic micro transmission mechanism was presented that can multiply the frequency of a reciprocating input motion. The mechanism is based on a compliant version of the double-slider mechanism, taking advantage of its singularity properties. Furthermore, by concatenating multiple of these mechanisms in a building block approach it was shown that higher frequency-multiplication ratios can be generated.

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