A Compliant Mechanical Frequency Dividing Transmission Using Parametric Oscillation

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***Abstract*—For small actuator driven systems, compliant mechanical frequency dividing transmissions could provide improved power density, with minimal losses. To our best knowledge, there has been no previous documentation on these types of transmissions. In this paper, two designs, based on parametric oscillation, are proposed and tested. The first concept uses a linear input at twice the output frequency, and splits it into two symmetric linear outputs. The other concept converts a linear input into a rotational output at half the initial frequency. Using Finite Element Analysis, the theory behind these concepts is verified. Prototypes were 3D printed and tested to validate the models. Results have confirmed that frequency division occurs. A resonance frequency region was determined, to evaluate the functional range of the dividers, showing that both systems function in a broad range of frequencies. This range indicates that the systems do not require resonance, and thus work with many frequencies, if the velocity near the dead-point is sufficient to push through this point.**

Keywords*— compliant mechanism; frequency division; transmission; parametric oscillation; eigenmode; frequency range

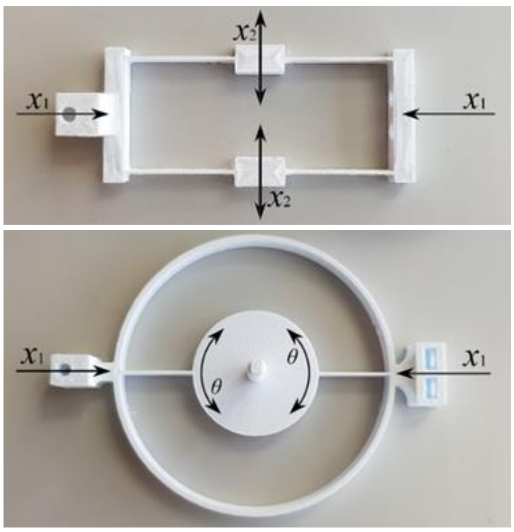
I. Introduction

Nowadays, frequency amplifiers, converters and dividers are commonly used in many different applications. These include, but are not limited to, energy harvesting systems [1], micro actuating mechanisms [2], and radio frequency transceivers [3]. For systems using small actuators, such as Flapping Wing Micro Air Vehicles (FWMAVs) [4], small mechanical frequency dividers, used as compliant transmission, would provide significant benefits for power output. They also have advantages over the standard electromagnetic frequency dividers. These systems yield a phase noise reduction and require less power to function [5]. Presently, compliant mechanical frequency dividers are limited in availability. Current designs are focused on phase noise reduction, which requires resonance with a high-quality factor (Q-factor). This demands a small frequency bandwidth of the resonator. Compliant frequency dividing mechanical transmissions would, however, require working with a wide range of frequencies. In this paper we set out to answer the question whether it is possible to design a compliant, large bandwidth frequency dividing transmission that functions on mechanical input. Two new designs of scalable compliant mechanical frequency dividers, using this type of input, are provided and have been tested.

To our best knowledge, there has been only one known mechanism, a 'micromechanical resonance cascade' [6], that can lower a mechanical input frequency by a factor of two or more. To accomplish this division, the system makes use of the principles of parametric oscillation and resonance. It is, however, limited in its use. For some applications, such as FWMAVs, a symmetrical transmission might be preferred due to, for example, its center of mass. Others might require a rotational output which cannot be realized with this design. A final point to consider is that this concept is focused on minimizing the frequency bandwidth. This is realized through the use of a 'parametric driver' with coupled resonators. In contrast, a mechanical transmission would preferably have a large bandwidth, due to high damping caused by the output.

II. Method

Based upon these requirements, we provide two new designs, both working with a direct linear input, namely the Linear Symmetric Frequency Divider and the Rotational Frequency Dividing Ring. In Fig. 1, pictures of both dividers are shown.



a) b)

Fig. 1. Picture of a) the Linear Symmetric Frequency Divider and b) the Rotational Frequency Dividing Ring. Driving force x_1 results in output displacement x_2 and output rotation θ respectively, at half the input frequency.

The Linear Symmetric Frequency Divider uses the principle of parametric oscillation to translate an input frequency to an output frequency equal to half the input frequency. The system input consists of two harmonic forces or displacements given by x_1. These forces drive the two weights in the middle of the beams parametrically at twice their natural frequency. From this, a resonating displacement, denoted by x_2, is created at the natural frequency of the weights. For testing, a natural frequency of 200 Hz or lower is preferred due to the available lasers. To lower the frequency, weights are designed to increase the mass of the oscillating thin beams. The beams themselves are designed to be as thin as possible (0.8 mm), limited by the used manufacturing process of Fused Deposition Modeling (FDM) 3D printing. The length of the beams is chosen such that the natural frequency is below the 200 Hz. To prevent any other undesired eigenmodes from activating, the larger beams have an increased thickness, parallel to the input. The two oscillating beams have enough distance between them to prevent collision of the weights during operation. Holes were added, to fasten the divider to the test setup.

The Rotational Frequency Dividing Ring uses the same principle of parametric oscillation. Two harmonic forces, given by x_1, are applied to the outside ring at two times the natural frequency of the center disk. This creates a rotation of the disk, given by θ, at its natural frequency. To lower the natural frequency, the beams are designed to be as thin as possible. The disk in the middle is chosen to be sufficiently large, to add enough mass for a natural frequency below the 200 Hz. The design of the outer ring is based on minimization of the force necessary to compress the ring, while still having a natural frequency that differs enough from the natural frequency of the disk, to prevent activation of unwanted eigenmodes. At the center of the disk, a pin was added to allow the attachment of a plane structure for testing. To fasten the divider to the test setup, holes were added.

Finite Element Analysis (FEA) is used to find the modes and frequencies of both designs. These designs, both make use of their first eigenmode, as shown in Fig. 2. Polyethylene Terephthalate Glycol (PETG) is used as material for the analysis [7]. This material was chosen due to the possibility to use FDM 3D printing for rapid prototyping. Compared to other general 3D printing materials, PETG provides high elasticity to get reasonably low natural frequencies for measuring, while still having high durability.

A transient analysis was performed to study the expected behavior of both designs, resulting in the responses shown in Fig. 3, where the normalized input force is plotted against the normalized output velocity. Both graphs show that there is indeed frequency division taking place for both designs.

To evaluate our designs, two protypes were manufactured from PETG, through FDM 3D printing. Fig. 4 shows a schematic representation of the setups used to test and measure these prototypes. An input displacement, described by an absolute sine wave, drives both designs parametrically. This input is realized through a spring pressing a pin against a rotating flower shaped disk with eight lumps. This disk is connected to a motor, generating eight displacements per rotation of the motor, allowing for higher input frequencies. The frequency of the motor is measured by an 'optoNCDT1402' laser pointed at a disk with one lump, connected to the shaft of the motor. The measured frequency is therefore one-eighth of the input frequency. This needs to be taken into account when analyzing the measurements.

The output displacement of the Linear Symmetric Frequency Divider is detected by an 'optoNCDT1420' laser, pointed at one of the weights. The output displacement of the Rotational Frequency Dividing Ring is detected using the same type of laser, pointed towards a rectangular face connected to the middle disk. All measured signals are processed by a 'National Instruments USB-6211' board connected to a laptop with the LabVIEW software.

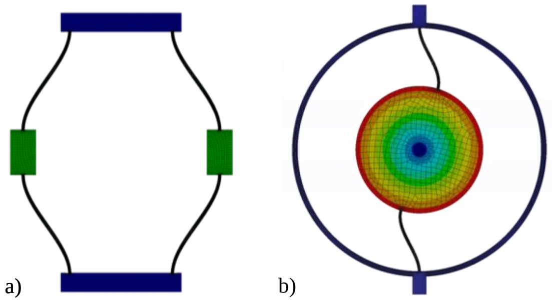


Fig. 2. Modal analyses, from ANSYS, of a) the Linear Symmetric Frequency Divider, at a frequency of 160.33 Hz, and b) the Frequency Dividing Ring, at a frequency of 166.98 Hz for the desired eigenmode.

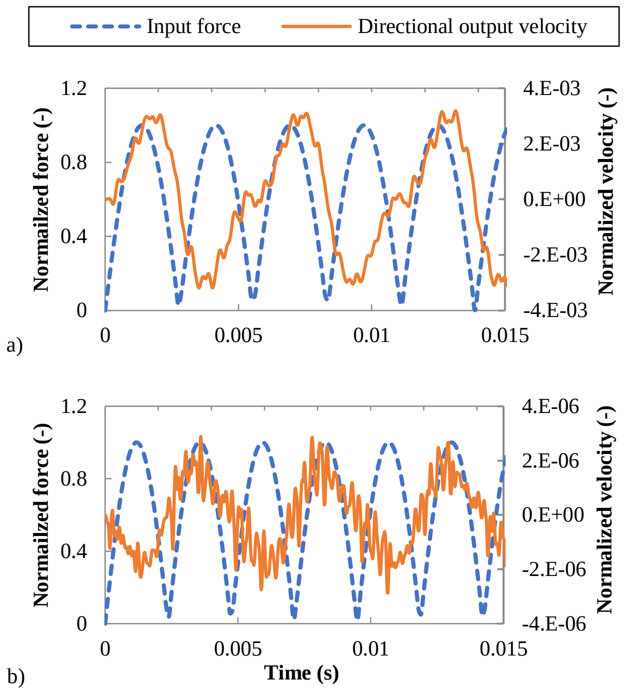


Fig. 3. The input force and output force over time for a) the Linear Symmetric Frequency Divider, and b) the Rotational Frequency Dividing Ring. The output frequency is half the input frequency.

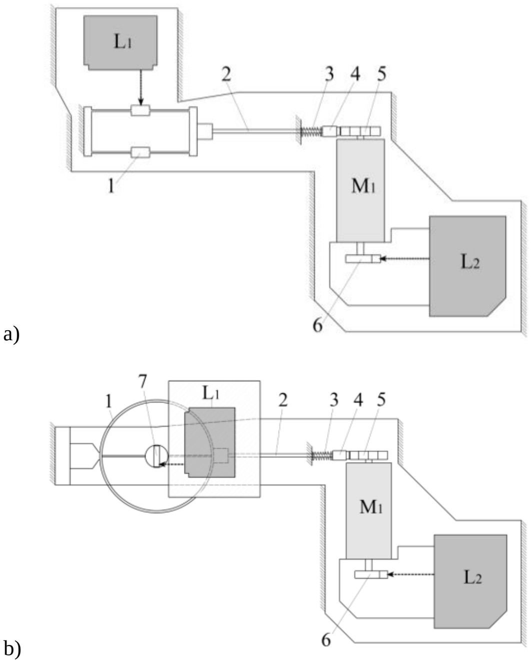


Fig. 4. Test setup of a) the Linear Symmetric Frequency Divider, and b) the Rotational Frequency Dividing Ring. The motor (M1) drives the flower shaped disk with eight lumps (5). A spring (3) presses the pin (2) and pinhead (4) against this disk, creating eight displacements per rotation. This displacement acts as an input for the designs. In a), a laser (L1) measures the output displacement of the Linear Symmetric Frequency Divider (1). In b), a laser (L1) measures the output displacement from a rectangular face, connected to the middle disk of the Rotational Frequency Dividing Ring (1). On the other side of the motor, a disk with one lump (6) is attached. A different laser (L2) measures a frequency from this disk, equal to one-eighth of the input frequency.

The modal response is observed through a sweeping of the input frequency, while the amplitude was measured real time at a sample rate of 320 samples per second. With this analysis, an optimal input frequency close to two times the natural frequency was derived from the maximum amplitude. To validate the occurrence of frequency division, a second measurement was taken at the optimal input frequency, with a sample rate of 40,000 samples per second.

III. Results

Fig. 5.a shows the input and response of the Linear Symmetric Frequency Divider. The input signal is described by an absolute sine wave, at twice the natural frequency of the oscillating masses. The measured output signal shows that frequency division is taking place.

Fig. 5.b shows the measured output signal of the Rotational Frequency Dividing Ring, together with an approximate input signal. Due to the test setup, the measured output signal consists of a combination of both the input signal, and the rotational output. The laser, used to measure this output, can only measure up to 200 Hz, while the input frequency is 352 Hz. Because of this, most displacements caused by the input are measured as a near constant offset. The rotational frequency is 176 Hz, making the rotational displacement still visible. Thus, the measured

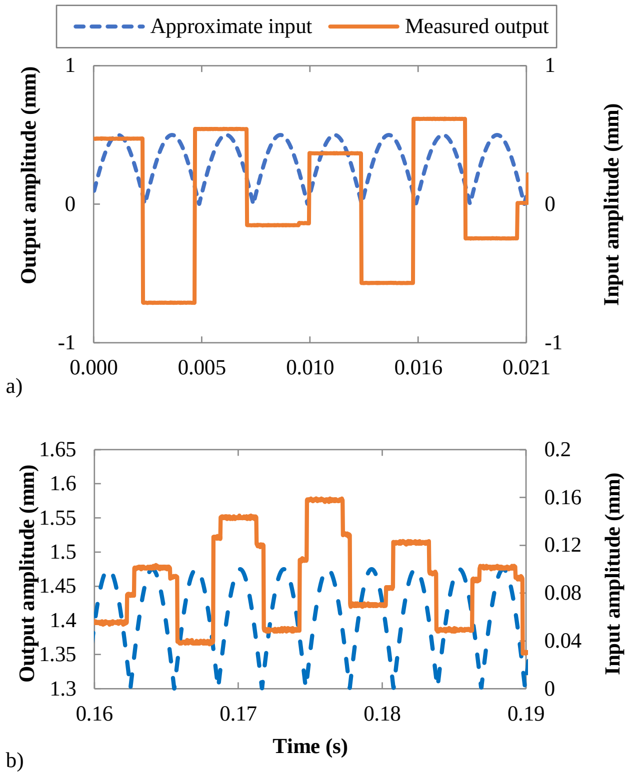


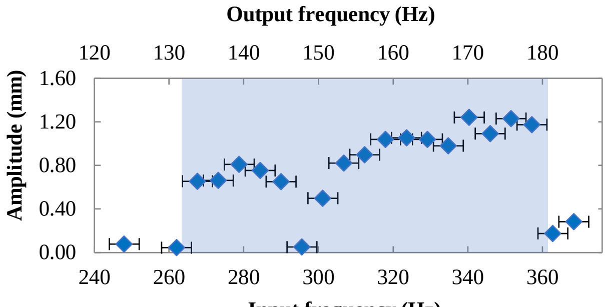
Fig. 5. The approximate input and measured response of a) the Linear Symmetric Frequency Divider, and b) the Rotational Frequency Dividing Ring. Both show that frequency division occurs.

sinusoid mainly consists of the rotational output, showing that frequency division occurs.

To determine the frequency region in which the desired vibrations of both designs are activated, the input frequency is swept along the range of interest at a constant interval. Fig. 6 shows the output amplitude as a function of the input and output frequency. The desired behavior is observed in the shaded area.

In Fig 6.a, a sudden drop in amplitude can be seen around 296 Hz. This drop was observed to be a sudden transition between two of the eigenmodes of the system. In the first of these eigenmodes, one of the masses vibrates with a slightly larger amplitude than the other one. Then, the mass that vibrates the least, experiences a sudden decrease in amplitude. After that, an increase in amplitude is seen again, while the amplitude of the other mass decreases slightly. This mode is similar to the first mode, but the amplitudes of the two masses have been switched. This slight difference in eigenfrequencies is caused by manufacturing errors. The figure shows that vibrations occur over a large range of frequencies, without clear resonance peaks, which means that the transmission has considerable damping.

In Fig 6.b, an offset can be seen in the measured amplitude. This is due to the amplitude not only containing the rotational resonating output, but also a constant input displacement caused by the test setup. The figure shows that also for this concept, vibration occurs over a large range of frequencies. This indicates that the transmission has similar high damping.



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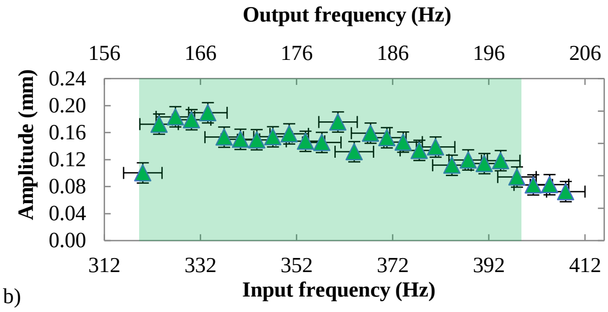

b)

Fig. 6. The frequency response of a) the Linear Symmetric Frequency Divider and b) the Rotational Frequency Dividing Ring. The shaded area shows the frequency range, where the systems vibrate. A large frequency bandwidth can be observed for both systems.

IV. Conclusion

In this paper we set out to answer the question if it is possible to design a compliant, large bandwidth frequency dividing transmission, that functions on mechanical input. Two designs of frequency dividers were presented and tested, the Linear Symmetric Frequency Divider and the Rotational Frequency Dividing Ring. The results confirm that the frequency is divided by two over a large frequency bandwidth, indicating that both designs would still function with high damping. Because of this, we can conclude that these two designs work with many frequencies, in the case that the velocity is high enough to push through the dead-point, thus allowing parametric oscillation. Since the designs are fully compliant, both should be scalable. For further research, production of a protype for use as a transmission in an actuation system is necessary. Additional research at microscale to validate the working principle, and research on the actuation stiffness of the designs, would also be recommended. Finally, stacking these designs for higher transmission ratios, and studying this combined behavior, might be an interesting follow-up.

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