Utilizing Mechanical Filters for a Single-Input Multi-Output Under-Actuated Mechanical System

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1. Abstract

The ability to transfer multiple independent signals over a single line has long been in use in the field of electronics and communication. Mechanical actuation is much simpler, with a single actuation input for every output. In this paper, we attempt to replicate the methods of electric signal transfer by using mechanical elements analogous to electrical components used in signal processing. We attempt to transfer several independent mechanical signals using a single actuator, and examine the inherent limitations in the transition from electronics to mechanical systems.

Keywords: Under-Actuation, Signal processing, Filters

2. Introduction

A basic assumption in the realm of mechanics is that for every independent mechanical output, there is a single input. This means that if there are five independent DOFs (degrees of freedom) in a robotic arm, for example, there must be five motors to drive these DOFs. This natural limitation can be cumbersome for systems with many degrees of freedom that therefore require a large number of actuators, especially if weight is a consideration. This is even more important when the weight of the actuators creates a cascading effect. For example, robotic arms with motors at their revolute joints must not only lift the weight of the arm and payload, but also the weight of the motors, requiring the motors to be more powerful, and therefore heavier-exaggerating the problem. Another example is robotic hands, which may require a large number of DOFs at the fingers, where space is limited, and weight is crucial. This has driven some robotic hand creators to push the motors towards the base of the robot, relying on remote power transmission methods such as cable driven transmissions [1].

The idea that only a single output can be achieved by an input is canon in the field of mechanics, but completely foreign in the field of signal processing. Multiple electrical signals are normally transmitted through a single medium, and deciphered as multiple outputs independently. A simple way of doing this is by transmitting each signal at a different frequency, where the amplitude of the signal wave represents the “information”. This is termed frequency modulation (FM), and can be observed in a common FM radio. Multiple signals are broadcasted simultaneously at different frequencies, but we can single out any one of them by focusing on the target frequency. In this case, the amplitude of the wave represents the audio information. This same principle can be transferred through wires.

If several electronic signals can be transmitted simultaneously and deciphered at the endpoint, one wonders why the same cannot be applied to mechanical signals. If a single actuator can
create a complex signal that is superposition of several signals, these could be separately deciphered and be used to control several independent DOFs, using a single actuator. This hypothesis is further encouraged by the fact that the electronic components used to filter signals each have analogous mechanical counterparts. Specifically, resistors, capacitors and coils can be translated to mechanical mass, dampers, and springs [2],[3]. This analogy holds due to the fact that these components have similar transfer functions.

Using FM, we can isolate specific signals by using a sequence of electronic elements. These include band-pass filters (BPF), rectifiers, and alternating current to direct current converters (AC to DC converters). These electronic components are comprised of resistors, capacitors, coils and diodes. Diodes can be mechanically analogized by using ratchet mechanisms, and the remainder can be analogized as aforementioned. This means that from a purely theoretical standpoint, mechanical filters are as possible as electric ones. This concept was researched by Penn [4], however experimental mechanical output analysis was not performed.

This work proposed the construction of a mechanical filter, in order to inspect the practical possibility of these filters. Real-world constraints will naturally limit the practicality of mechanical filters, and therefore it is the aim of this work to detect the limitations of such a filter, and better understand the dynamics involved.

The constructed mechanical filter will represent the first stage of signal isolation. Specifically, the experimental setup will generate a complex signal, and attempt to filter the signal using an analogous BPF. An ideal BPF is one that allows perfect permeation of the desired frequency, while completely damping lower or higher frequencies. The frequencies that a BPF permits are a function of the values of the circuit’s resistors, capacitors and coils.

3. Contributions

An experimental setup is constructed with a single Dynamixel MX-106 servo motor, directly connected to three mechanical BPFs. Each BPF is comprised of a rotational spring, and an adjustable mass. Each BPF output is measured by a rotary potentiometer. Several experiments are conducted to determine the system response to different signals.
Each BPF is designed to permit specific frequencies, with minimal overlap. The resonate frequency for each BPF is defined as:

\[ f = \frac{1}{2\pi} \sqrt{\frac{k}{J}} \]

where \( f \) is the resonate frequency, \( k \) is the spring stiffness coefficient, and \( J \) is the inertia.

The motor generates a variety of sinusoidal waves with varying frequencies, and the system response is logged. A permission of the signal results in a BPF entering resonance. This is because the constructed BPF is a simplified version without damping, in order to clearly determine system response with minimal expulsion of energy in the system. Dampened signals are typically significantly lower, and we expect no movement of an ideal mechanical BPF in response to a signal outside its specific bandwidth.
Figure 2. Experimental results, response of each BPF to signals with different frequencies.

4. Conclusions

The experiments show that using the current setup, no more than five simultaneous signals may be conveyed at once. This limitation is given by an upper frequency limit imposed by the motor (slow inertial response), a lower frequency given by the natural friction of the system that dampens these low frequency signals, and the bandwidth of each filter.
Figure 3 setup. Best-case projected filter results using the experimental setup.

This result shows us that while mechanical filters are possible, their practicality is limited. We must remember that the experimental setup only comprises the first stage of true signal filtration, and every subsequent stage (rectification, AC to DC conversion) introduces further disturbance to the system, limiting the practical number of distinct frequencies.

Future work should focus on finding the effects of miniaturization of the system to reduce undesired inertial effects, as well as introducing subsequent signal filtration stages.

A full analysis of the system can be seen in the project documentation in the Department of Mechanical Engineering, Ben-Gurion University of the Negev [5].

5. References

Sample references are given below (10 pt):