

Project Number: ECC-C007

Self-Synchronous Vibration Testing Mechanism

A Major Qualifying Project Report

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Abstract

This project was created to demonstrate the phenomenon known as self-synchronization using motor-driven, unbalanced rotors mounted on a spring-mounted base. A mechanism resembling that used by scientists who first studied the phenomenon was constructed and used to successfully reproduce the desired effect. Some modifications, including the removal of key components, were deemed necessary to obtain satisfactory results.

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1: Introduction

The purpose of the design to maintain rotation of unpowered shafts through vibration was to design and manufacture a mechanism that demonstrates the self synchronization phenomenon.

The goal of the project was to design and manufacture a mechanism that would demonstrate self-synchronization of unbalanced shafts through vibration. Figure 1 shows the completed mechanism with leaf springs attached.

The design project began with an attempt to replicate Mekhanobr's design but replacing the rubber shafts with metal leaf springs to make the vibrating part move in only one dimension. Throughout manufacturing, building and testing, some components were replaced due to financial constraints or due to time constraints. The design similar to Mekhanobr's rig with its alterations was tested and failed due to some choices of components that there was no knowing of how it may affect final results. After observing the reasons why our first design failed, a different design was concocted on the spot and rebuilding was made in less than a day. With the assembly of the final design and the test run, the new design was successful in achieving the main goal of the project; demonstrating self-synchronizing mechanisms.

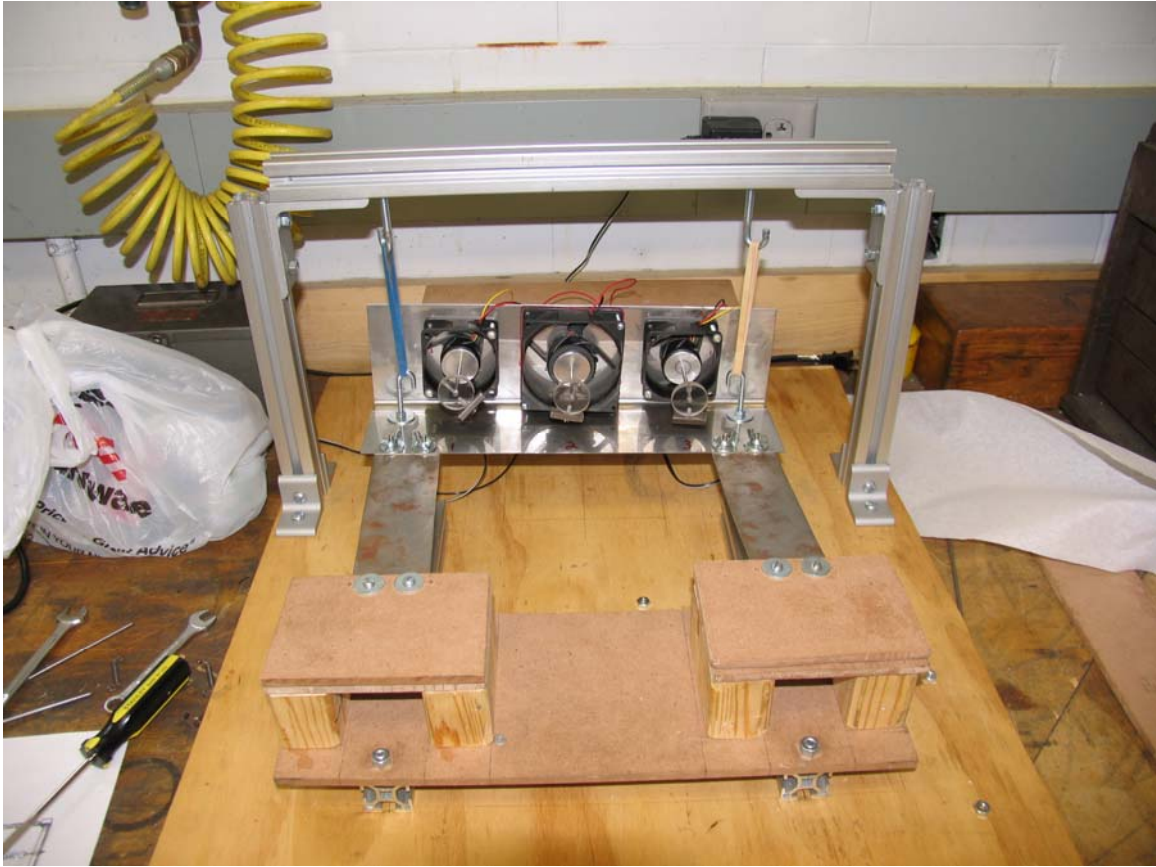


Figure 1 - Self-Synchronization Mechanism

2: Background

The Major Qualifying Project (MQP) design concept was based on a mechanism created and tested at the Mekhanobr Institute in St. Petersburg, the site of the first observation and experimentation of self-synchronization in unbalanced rotors. The use of self-synchronization of unbalanced rotors has led to hundreds of designs that utilize vibration as a primary form of operation, such as conveyers, screens, and crushers (Blekhman, 2000.)

2.1 Self-Synchronization

The term self-synchronization refers to a phenomenon caused by vibrations in unbalanced rotors. The first recorded observation of this phenomenon was made by Christian Huygens sometime in the late 1600s. Huygens hung two pendulum clocks from the beam of a boat and discovered that, while the clocks had previously run at different rates, their pendulums eventually began to swing in synch and would tend to return to this manner when one or both pendulums were disturbed. Huygens determined that this phenomenon was due to the motions of the beam, which transmitted the vibrations created by the pendulums from one clock to the other, forcing them to oscillate in synch (Blekhman, 1988.)

It wasn't until 1947 that the synchronization phenomenon for mechanical unbalanced vibro-exciter was discovered during a research project led by D.A. Pliss in the Mekhanobr Institute. When two unbalanced rotors driven by separate induction motors were mounted side-by-side on a fixed platform, they invariably ran at different angular velocities due to uncontrollable differences in the construction of the motors. However, when these same systems were mounted together on a vibrating foundation, it was discovered that they would run at an average velocity and in synchronous motion. Furthermore, the rotors would tend to maintain this behavior even when the power to one motor was cut off, as it happened when the power supply cable to one of the motors was accidentally severed but not discovered for a number of hours, since the rotors continued to spin in synchronous motion. Figure 2 is a drawing of the three-shaft mechanism created by researchers at the Mekhanobr (Blekhman, 1988.)

Synchronization can be observed in many everyday events. For example, humans walking side by side tend to walk “in step” with one another after a short time, applause from a large audience tends to transform into more or less a “single” clap, and wing strokes of birds in a flock will synchronize, as will fin strokes in schools of fish and flashes produced by fireflies.

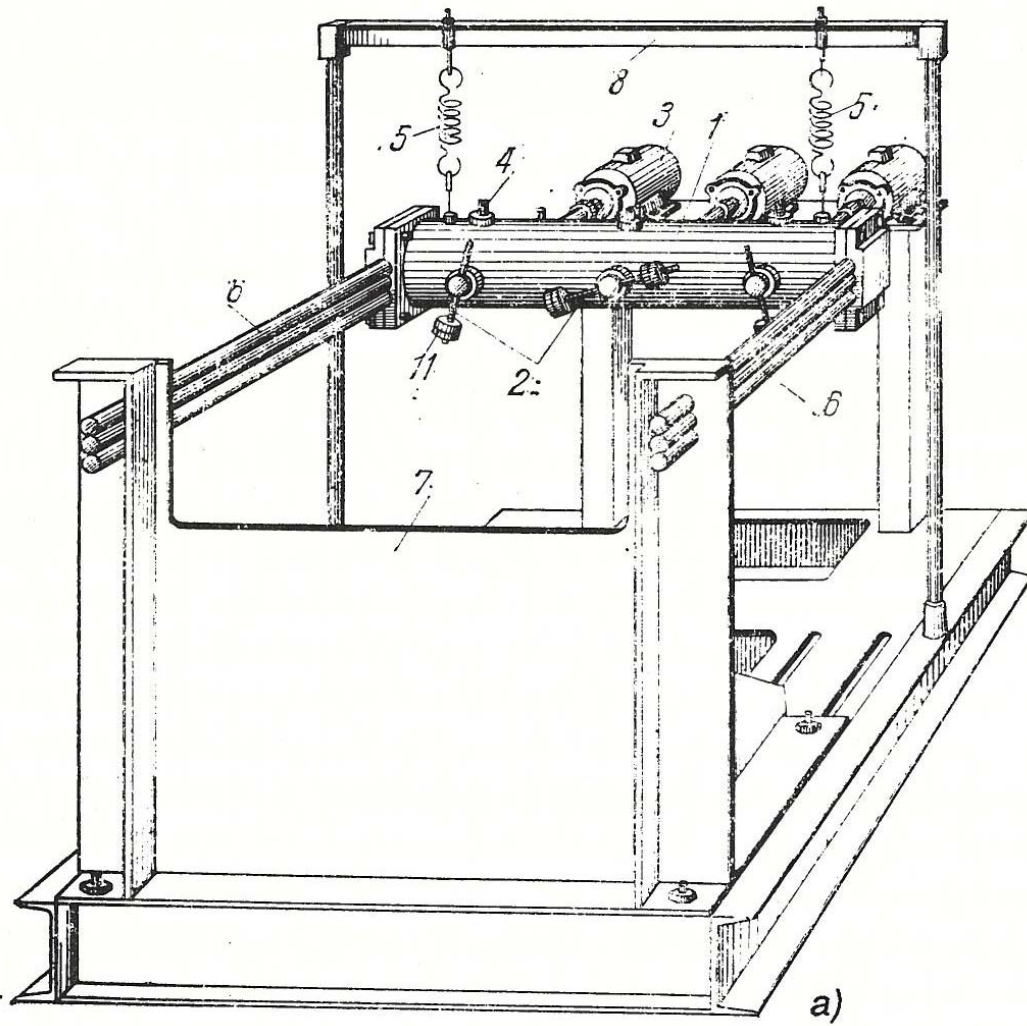


Figure 2 - Mekhanobr rig showing three unbalanced rotors connected by a rigid vibrating pipe.

2.2 Task Specifications

- The finished mechanism should be sized to allow for easy transportation
- The mechanism should be stable and safe to operate.
- The mechanism should demonstrate the self-synchronization phenomenon.
- The mechanism should utilize three motors driving unbalanced rotors.
- The motors must be brushless and allow for resistance-free back-drive.
- The motors should be powered from a standard wall outlet.
- The design should allow for the removal of the leaf springs from the vibrating platform.
- Overall cost should not be more than \$100.

3: Theoretical Design

This project is based around the Equations of motion for similar unbalanced shafts:

$$m\ddot{x} + 2\alpha m\dot{x} + Kx = m\ddot{\theta}^2 \cos 2\theta + m\epsilon\ddot{\theta} \sin \theta$$

The theory involves two motors spinning unbalanced shafts at different angular velocities. If the shafts are connected in some way through a block of material (or they share a base) then the vibrations created by each unbalanced rotor will have an effect on the other rotor, causing the two to synch up and rotate at the same average velocity. When one of the motors is turned off, the vibrations from the remaining unbalanced rotor will cause the unpowered rotor to continue rotating at the same average velocity (at which the powered rotor will continue to turn as well.)

The original design of the mechanism involved the use of thin, rectangular pieces of metal (leaf springs) to serve as the supports for the platform upon which the motors and unbalanced shafts would be mounted. The leaf springs were intended to allow the platform to vibrate with minimal outside damping, while limiting the range of vibration to side-to-side motion. However, the book *Synchronization in Science and Technology* offered a clearer design which replaced the original. In this iteration, the rotating shafts were mounted through a length of pipe that was suspended by extension springs and therefore independent of any outside vibrations. The shafts were connected to the motors by flexible couplings. The vibrations produced by each shaft would travel through the pipe and affect the rotation of the other shafts, producing synchronization.

Furthermore, the pipe was supported on the ends by lengths of stiff rubber tubing, arranged in such a way to allow the pipe to vibrate in only one direction. This part of the design was altered in the final mechanism – instead of using rubber tubing, leaf springs were mounted on the underside of a length of square aluminum stock (the shape of the material is arbitrary as long as vibrations are transferred between shafts) allowing the pipe to vibrate vertically.

After some testing, it was decided that the couplings used to join the motors and shafts were causing unwanted dampening that was interfering with the rotation of the shafts, so the square stock was removed, the shafts were shortened, and the motors were

moved onto a platform that was suspended in place of the pipe. This way, no flexible couplings were necessary and the shafts could be cut to much shorter lengths, reducing any flex that occurred when rotating.

3.1 Materials

Normally, materials would be chosen with attention paid to weight and cost. For this project, the majority of materials used were obtained at no cost from the Higgins Labs machine shop, nullifying the issue of cost. Furthermore, weight was not an issue where most of these materials were involved, the exception being the weights on the ends of the rotors.

3.1.1 Steel

Steel has excellent strength and hardness, and is relatively inexpensive. However, it is heavy, limiting its use where weight is an issue.

3.1.2 Aluminum

Aluminum is relatively lightweight and, in most instances, possesses sufficient strength for the purposes of this mechanism.

3.1.3 Pine

Pine is lightweight and easy to manipulate, as well as very cheap and easy to obtain, and suits the requirements of this project well.

3.1.4 Fiberboard

Like pine, fiberboard is easy to obtain and machine, and is very inexpensive. It was used as a flat mounting surface for both the motors and the leaf springs, and is more than strong enough to support any stresses that may occur.

3.2 Material Comparison

As previously stated, choice of materials was only limited by availability. The design of the mechanism did not present any requirements that could not be met with the available resources.

4: Physical Design and Manufacturing

Most materials were obtained from the machine shop located in Higgins Labs, at no cost. Other components were purchased from different vendors. Motors were obtained from Jameco Electrical Company.

4.1 Component Selection

Since most components don't have much effect on the system, but rather are more of mounts and supports. We used whatever was available in the machine shop to reduce the cost of building the mechanism. Specific selections of components are described below.

4.1.1 Electric Motors

Choosing proper electrical motors was crucial to the mechanism. Of the many different types of motors that were available, choices were limited to the few types that would meet the specifications of the design, which included rotational velocity (above 2000 RPM) and minimal resistance when back driven. The different types considered were regular DC-Motors, DC-brushless motors, and AC induction motors.

Regular DC motors were considered mainly due to their low cost. These motors would allow some back-drive but with some resistance. Regular DC-motors use a commutator that is mounted onto the armature (rotating shaft) that would bring electrical current to an iron core with wire coils wound around it to induce electromagnetic field which, with the help of a permanent magnet mounted in the casing of the motor, would create an EMF force that would rotate the armature. The commutator is connected to outside electrical source by means of a brush. This brush provided the most resistance to the armature to being back driven.

In addition to the price, this motor would also create an electrical current when the shaft is driven externally. This would have helped in the analysis of the design and calculation of power conversions to easily calculate power losses. Also, the speed of the motor could be controlled simply by controlling the supply's current or voltage.

Brushless-DC motors were considered because they had very low resistance to being back-driven. Usually used on computer fans, these motors provided more than

enough speed for the project's purposes and extremely low resistance to being back-driven. These motors operate differently than the regular DC motors. Unlike the regular DC-motors, the permanent magnets are built right onto the armature, with the steel core and coil built onto the stationary part of the motor. The armature is simply the permanent magnet held together by a molded plastic that is mounted onto a shaft that is kept in place by rotational ball bearings. The only resistance felt when turning the armature by hand was the magnet's pull on the steel core, which was too small to affect the mechanism.

However, these specific types of motors operate by converting DC current into quick pulses of electrical current with the use of internal circuitry, causing the armature to move at a single speed. Varying the speed of the motor was not an option.

The third and last choice of motors were the AC-induction motors. These motors were the type suggested by Blekhan in *Synchronization*, in an attempt to reproduce the experiment designed at the Mekhanobr. AC induction motors provide the least resistance to back-drive, mainly because the armature is simply freely rotating with no connection to the stationary part of the motor other than bearings - not unlike the DC-brushless motor. However, instead of a permanent magnet, coils are used to create a changing magnetic field on the stationary part, which also in turn induces current onto small wire loops built onto the armature.

With no current and voltage supplied to the motor, there is even less resistance than found in a brushless-DC motor. In addition, this motor's speed can be controlled simply by creating a controller that can alter the power source's frequency. However, due to the operational method of this motor, directly measuring rotational speed from synchronization is not possible, since there will be no current induced from armature's rotation.

The induction motor was not considered further due to prices of motors and controllers being beyond the budget of this project. The first two types of motors were tested, however. The brushed DC-motor proved to provide too much resistance to the mechanism, causing all rotors to simply stop whenever their corresponding motors were turned off.

In order to use the brushless-DC motors, the motor mounts required modification. With that came a whole new concept of mounting the motors onto the vibrating part of

the mechanism. This gave results which demonstrated the effects of self-synchronizing mechanisms and also proved that even in one-dimensional movement self-synchronization can be achieved. Figure 3 shows the motors and the re-designed mount.

Figure 4 shows the computer fan prior to its modification to be used in our mechanism. The most notable change is the removal of the blades of the fan. The blades had no effect on the system as a whole, but it was found initially that during operation some of the blades would bump onto the frame due to deviation while vibrating.

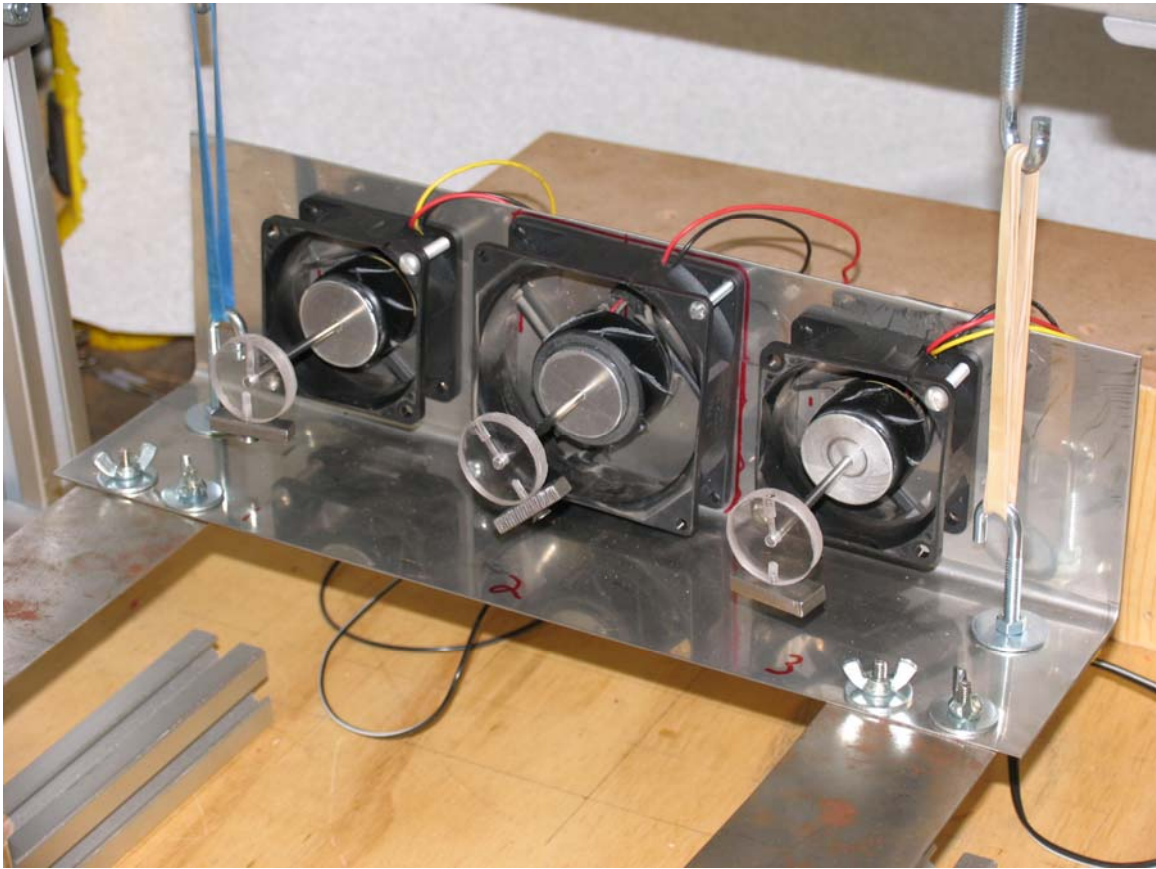


Figure 3 - Close-up of the motors and unbalanced shafts mounted on the vibrating platform.

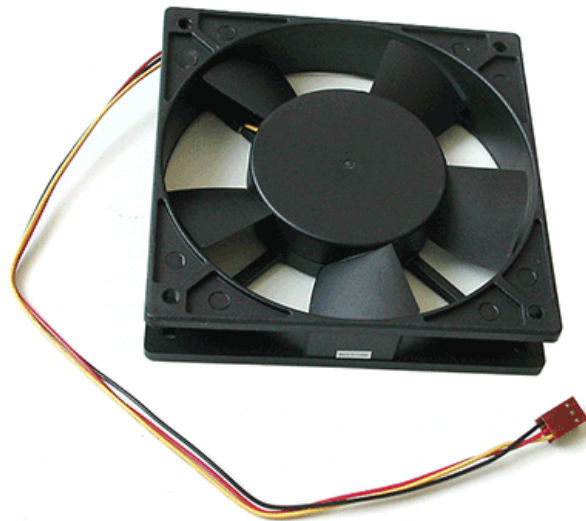


Figure 4 - Computer fan using a brushless-DC motor was modified for the use of this project.

4.1.2 80/20 Framing System

Both the track for the leaf spring mount and the vibrator platform frame were constructed from pieces of 80/20 framing system. 80/20 framing is made from 6105-T5 aluminum alloy with a yield strength of 35,000 pounds per square inch, and features an extruded rail shape that makes it useful for constructing a sturdy frame. Scrap lengths of the 10 Series T-slotted 80/20 (with a 1" square profile) from the machine shop were cut to length and assembled with spare L-brackets from 80/20 Inc. to form the frame for the vibrator platform. Two 11" lengths of 80/20 were connected by two 2-hole L-brackets to a 9" length of aluminum L-channel to form the H-frame for the track upon which the leaf spring mount sits. Figures 5 and 6 shows the 80/20 and the L-channel aluminum bolted to the base.



Figure 5 - H-frame track for leaf springs mount.

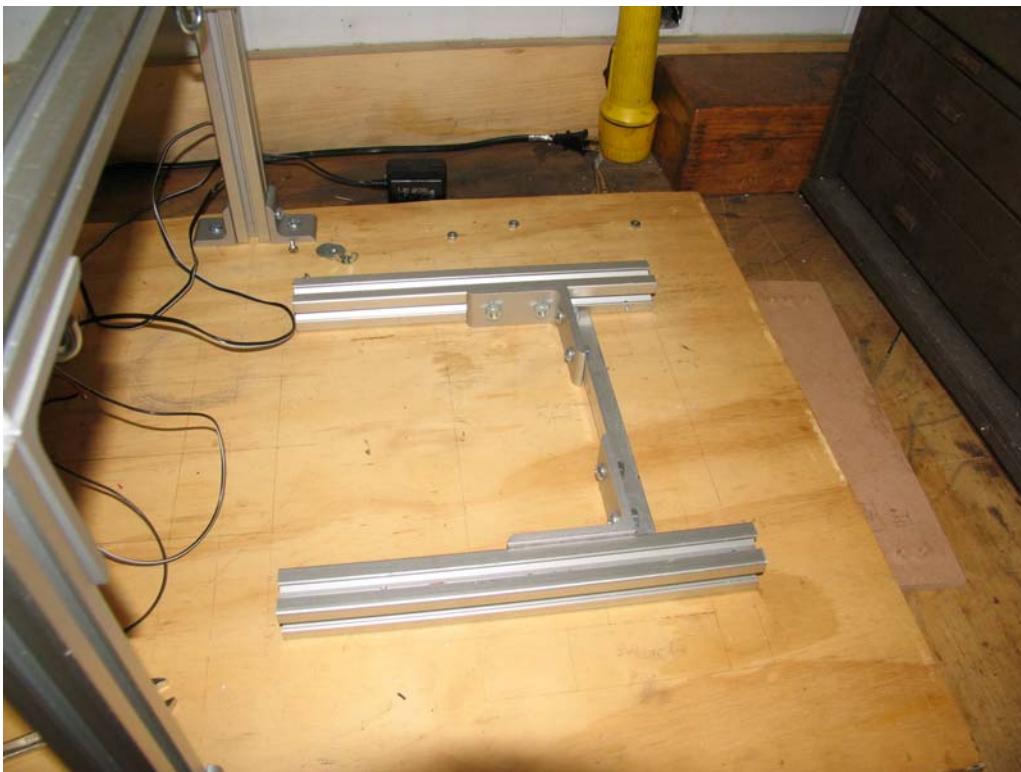


Figure 6 - Another view of the H-frame.

4.1.3 Springs

Originally, springs were selected to support the square aluminum stock, but were later replaced with rubber bands to support the vibrator platform. The elasticity of the bands was deemed unimportant as long as they held the platform clear of the base. The rubber bands actually seemed to work much better than the springs, since they contributed almost no damping to the mechanism, whereas the springs seemed to have a small effect.

4.2 Manufacturing

All manufactured components were created in the machine shop located in Higgins Labs, and most material (unless noted otherwise) was obtained from the supply closet in the machine shop. Machines used included a three-axis milling machine, drill press, handheld jig saw, band saw, and various small hand tools.

4.2.1 Leaf Springs

The leaf springs were machined out of 22GA welding steel (approximately 1/40th of an inch thick) and provided the necessary flexibility and strength to support the vibrator platform with minimal dampening.

4.2.2 Shafts

The rotating shafts were machined out of a 36 inch length of steel rod, 3 millimeters in diameter. The diameter was arbitrarily chosen, taking into account size considerations for the motors and overall mechanism.

4.2.3 Unbalanced Weights

The unbalanced weights were machined out of pieces of scrap steel obtained from the Higgins Labs machine shop. Sizes varying by a few millimeters were manufactured and then tested to find the weights that produced the best results. Figure 7 shows a closer view of one of shafts with the weight attached.

4.2.4 Vibrator Platform

The vibrator platform consisted of a 6.5"x13" piece of sheet steel, which was bent into two sections: the bottom, which was 3"x13"; and the back, which was 3.5"x13", and was the surface to which the motors were mounted.

4.2.5 Platform Frame

80/20 was used to build the frame that would support the vibrator platform and isolate it from any outside vibrations. Easy to manipulate and construct, proper T-nuts (used to attach lengths of 80/20) were not available, but hex nuts and button-head bolts were substituted with satisfactory results.

4.2.6 Switch Mount

Originally intended to be the mounting platform for the motors, it is constructed out of two 4" lengths of 2'x4' (which serve as the supports), a 4"x12" piece of fiberboard on which the switches are mounted, and a 3.5"x12" piece of fiberboard attached to the tops of the supports. Figure 8 shows the switch mount.

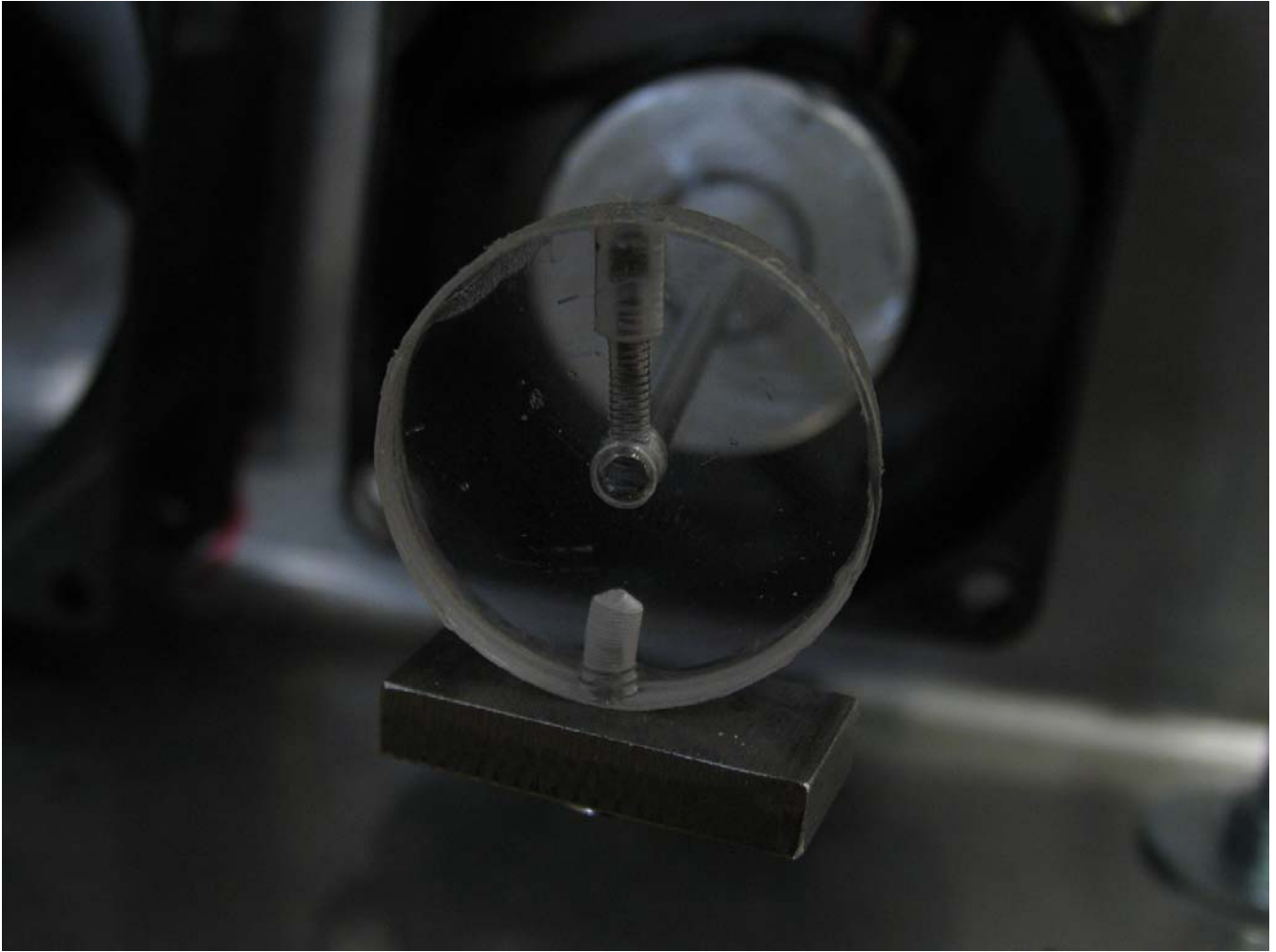


Figure 7 - Close-up of shaft and weight

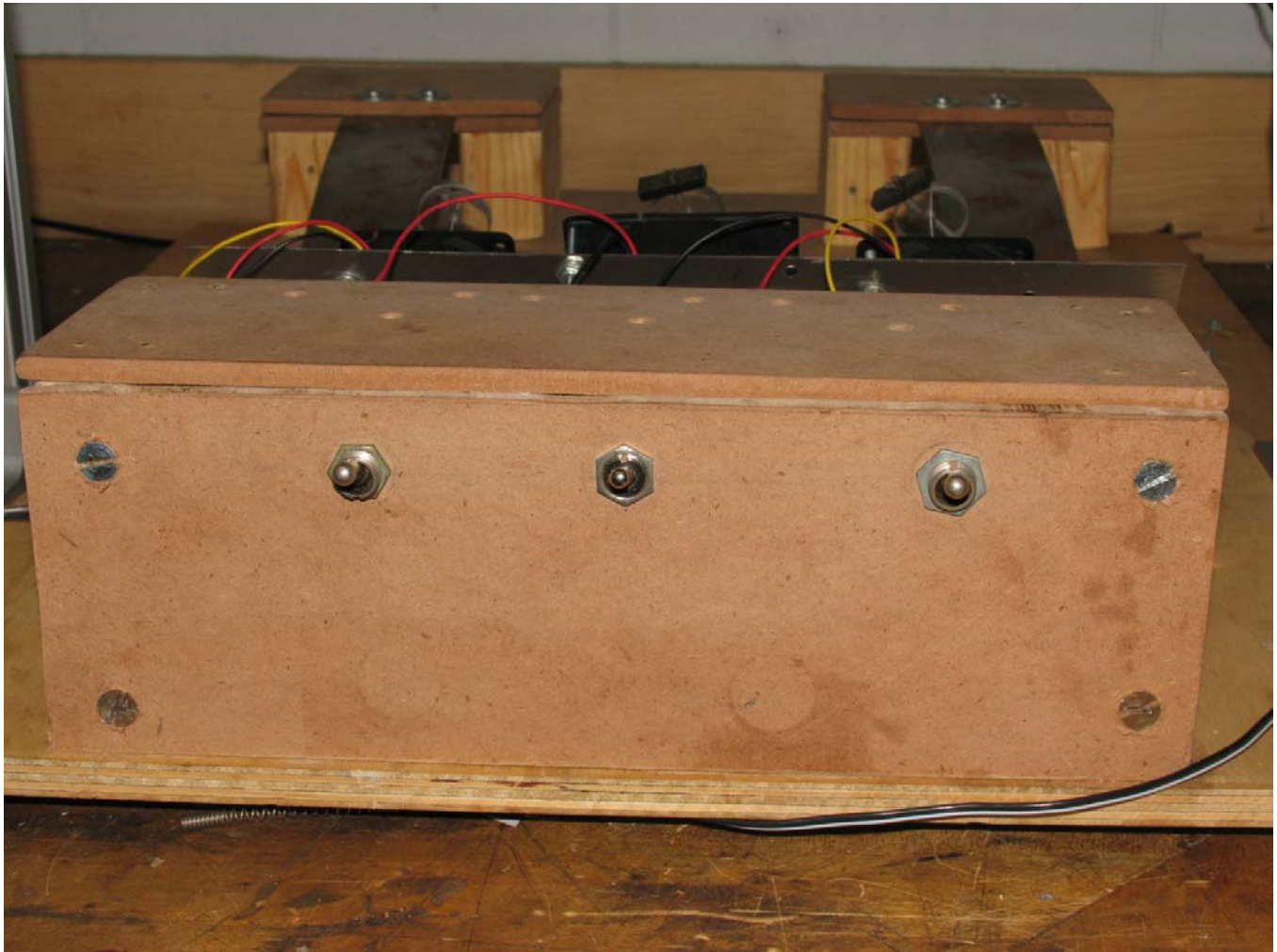


Figure 8 - A mount was made to place the switches that controlled which motors to provide power to or which to cut power to.

4.2.7 Leaf Spring Mount

The leaf spring mount was constructed out of a fiberboard base (5.5"x15") upon which were mounted four 2" lengths of 2"x4", each pair of which served as supports for a 3.5"x5" piece of fiberboard where the leaf springs were attached. Each leaf spring was sandwiched between its base and a second piece of fiberboard to equalize above- and below-plane flexing when the mechanism was in operation. Shown in Figures 9 and 10 are the leaf springs bolted into the mount.

4.2.8 Base

The base upon which the entire system was built was a 21.5"x25" piece of plywood. Holes were drilled to mount the various components of the mechanism: the vibrator frame, the leaf spring track, and the switch mount supports.

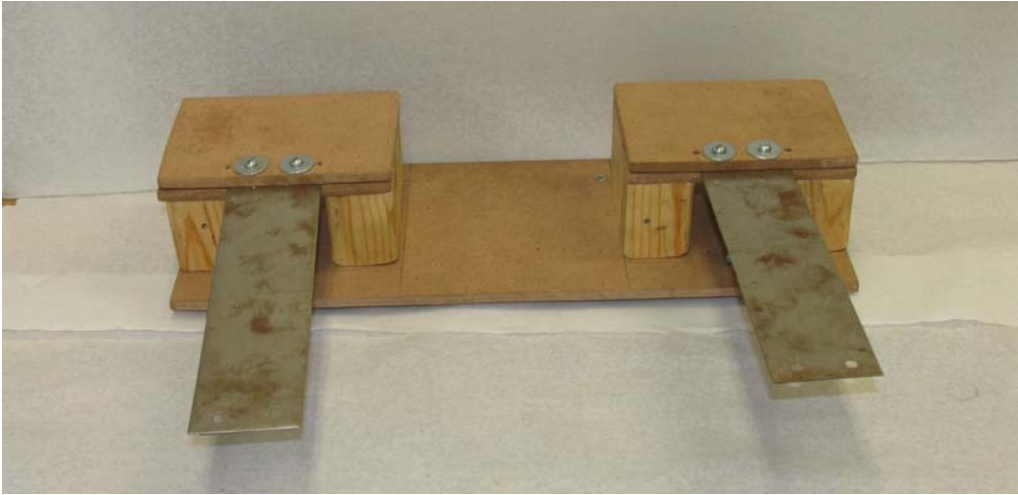


Figure 9 - Leaf springs bolted on mount.

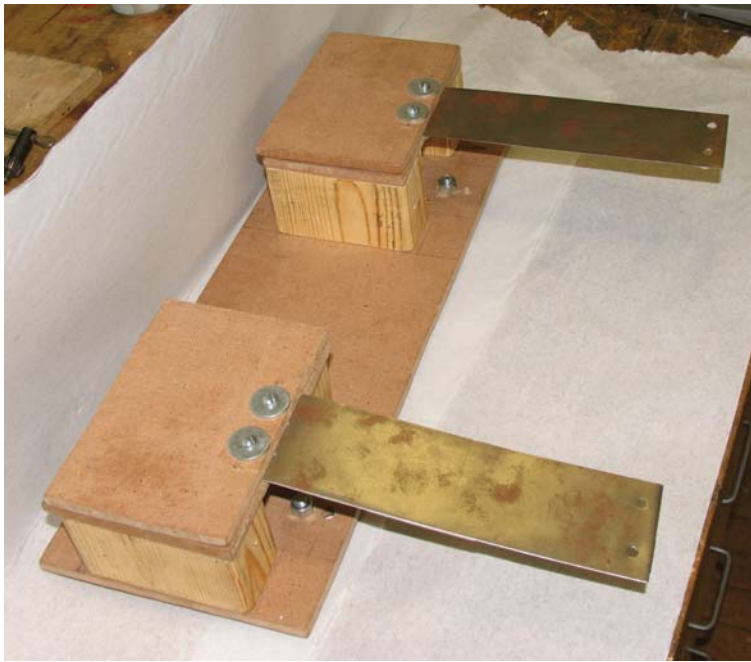


Figure 10 - Another view of leaf springs and mount.

5: Testing and Results

Once construction of the first design iteration was complete, testing began on the mechanism. After a number of runs, the design was clearly not working properly. It was determined that the rotors would not synch up because of too much vibration.

Furthermore, the motors offered too much resistance to allow the unpowered rotors to spin freely. The flexible spring couplings between the motors and the shafts were affecting shaft rotation as well – the shafts were flexing too much and rotational velocity was not being properly transferred from the motor to the shaft.

The motors were replaced with the computer fan motors discussed in section 4.1.1, which presented much less resistance to allow the unpowered rotors to spin freely. To solve the problem with the spring couplings, the couplings were eliminated entirely, along with the vibrator pipe. The system was simplified by placing the motors, along with the unbalanced shafts, directly onto a vibrator platform that was suspended by springs. The unbalanced shafts were cut to four inches in order to reduce flexing during operation, but length and too much weight on the ends were still causing problems, so the weights were reduced and the shafts were shortened by one inch.

Theoretically, the self-synchronization mechanism should allow for three unbalanced rotors (spinning at different angular velocities) to synch up and rotate at the same average velocity while all three motors are running. When one or two motors are shut off, the remaining active motor and its unbalanced shaft should produce vibrations that will cause the two unpowered rotors to continue spinning, and all three rotors will still be rotating at the same average velocity.

After some tweaking of the mechanism, all three rotors were able to synch up and spin at the same velocity while powered. When two of the motors were turned off, their rotors (and the third, powered rotor) continued spinning at this average velocity. Interestingly, this only occurred once we removed the leaf springs, and the explanation for this is discussed below.

The purpose of the steel leaf springs is to contain the vibrations of the vibrating component within the vertical plane of motion, that is, it should be limited to up-and-down vibrations. Theoretically, this should be enough to cause unpowered rotors to rotate in synch with the powered rotor. Instead of limiting motion to the vertical plane,

the leaf springs actually caused the entire platform to shake in a diagonal motion, where one end of the platform would be traveling to its lowest point of flex, while the opposite end would be reaching its highest point of flex. The leaf springs would be effective if the two small motors mounted on the ends of the platform had equally balanced rotors and were started not only at the same time, but in the same position. This would allow the leaf springs to flex up and down in a synchronized manner.

6: Conclusions and Recommendations

While the design concept for this project began as a slight alteration of the design discussed by Blekhman in his book *Synchronization*, it is possible that because it was a slight alteration to begin with that it ended up being noticeably different at the conclusion of the testing. While the original Russian design used rubber shafts to support the vibrator pipe, this design used horizontally mounted steel leaf springs which seemed to dampen vibrations enough to prevent synchronization from taking place. This, along with the use of springs instead of flexible couplings necessitated the replacement of the vibrator tube with a platform and the repositioning of the motors from the stable mount to the platform itself, changes which seem to have had a positive effect on the experiment.

In a sense, the system created for this project is an alteration of a number of figures appearing in Blekhman's text: figures showing unbalanced rotors and motors mounted on a surface that is supported completely by a base of springs. The similarity is obvious – one is supported by springs from below, the other suspended by springs from above, but the result is the same – negligible dampening effect on the vibrations caused by the unbalanced rotors.

In the interest of time, certain simple additions were neglected without any negative effect on the results of the project. For example, instead of soldering the wiring for the motors, standard connectors could be installed, allowing for quick connection and disconnection. Small LEDs could be wired into the circuit to indicate which motors are powered and which are off. Also, because this mechanism uses brushless-DC motors with built-in circuitry, the ability to change rotor speeds are inhibited. These motors could be replaced with AC-induction motors and an external controller that can alter the frequency of the alternating current to which end would create a speed controlled motors. If all three induction motors were connected to the same source then we can always be sure that all three are in sync with each other. However, separate controllers can be made for each induction motor to demonstrate effects of different angular velocities with the synchronizing phenomenon.

Overall this project went as well as could be expected, but there is always room for improvement. One example is the lack of experience in vibrational mechanics on the

part of the students. This project presents an opportunity to revisit the self-synchronization phenomenon, either with the same students (after having gained some experience in vibrational mechanics) or with new students who have prior experience. There is a definite opportunity to refine the mechanism and guarantee that it works reliably and as effectively as possible. Furthermore, the project could be altered to fit the original design concept involving leaf springs as sole supports of the base, upon which the motors and shafts are mounted. This would provide a better analysis of the phenomenon.

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Appendix: Component specs

12VDC Motor

- ◆ Manufacturer: Nichibo
- ◆ Voltage Range (VDC): 6-12
- ◆ Current (Amps): 0.24
- ◆ RPM (max.): 7050
- ◆ Torque (g-cm): 19.5
- ◆ Terminal Type: solder
- ◆ Shaft Diameter: 0.078"
- ◆ Shaft Length: 0.314"
- ◆ Size: 0.944"D x 1.063"L

Jameco P/N	231976PS
Mfg	JAMECO RELIAPRO
Mfg #	UC-260-12335
RoHS?	No , Find compliant
In Stock	N/A
Nominal Voltage (VDC)	12
Size (Dia)	0.944 x 1.063
Voltage Range (VDC)	6-12
Current @ Max. Efficiency (A)	0.24
Speed @ Max. Efficiency (RPM)	7050
Torque @ Max. Efficiency (g-cm)	19.5
Efficiency	50
Terminal Type	Solder
Shaft Diameter (inch)	0.078
Shaft Length (inch)	0.314

MOTOR,DC,6-12V,7050RPM,0.2A,
19.5G-CM,1.4W,SHFT 02X8mm



# of Units	\$US EA
1+	1.15
10+	1.05
100+	0.95

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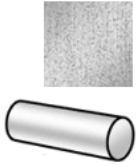
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Steel

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\$1.67 Each

Material	General Purpose Water-Hardened W1 Tool Steel
Finish/Coating	Decarb-Free
Shape	Rods and Discs
Diameter	1/8"
Diameter Tolerance	±.0005"
Length	36"
Length Tolerance	+1/8"
Straightness Tolerance	.005" per foot
Tolerance	Standard
System of Measurement	Fractional Sizes
Temper/Condition	Annealed
Hardness	Brinell 241
Maximum Attainable Hardness	Rockwell C60
Yield Strength	50,000 to 100,000 psi
Application	Drill Blanks and Rods
Specifications Met	American Society for Testing and Materials (ASTM)
ASTM Specification	ASTM 686