Final Technical Report:  
Vibration Analysis and Shaft Alignment Training Devices  

By:  
Aden George-Warren, Ben Harris, Parker Johnson, Deric Kang, Chenxi Liao, Steven Marshack
I. Executive Summary

The purpose of the Vibration Analysis Device (VAD) and the Shaft Alignment Device (SAD) is to allow the customer, M.C. Dean, Inc., to train their employees in-house to use highly sensitive vibration and shaft alignment sensors to diagnose and correct machine unbalance and misalignment for predictive maintenance. With respect to analyzing vibrations, the customer requires a device that can not only provide vibrations, but also contains a mechanism for completely eradicating them from the machine. The VAD provides this mechanism in the form of a balance rotor. By placing different weights along various positions on the radius of the balance rotor, the vibrations in the machine can be completely dampened. The SAD, on the other hand, must be capable of offsetting two shafts both axially in the vertical and horizontal direction, as well as angularly. Through the use of horizontal and vertical lead screws, each tower can be individually adjusted while the flexible coupler allows for the two shafts to remain connected. After connecting the respective sensors to each device and operating the machines the desired effects were achieved and both systems allowed for the detection and correction of unbalance and misalignment, respectively.
II. Introduction

A. Scope: Vibration Analysis Device

Vibration can be defined as oscillatory motion of a machine or machine component about an equilibrium position. Vibrations are generated by the input of external forces on a mechanical system and can be described in terms of displacement, velocity, and acceleration [1]. The goal of vibration analysis (VA), as applied to maintenance of machinery such as pumps, fans, turbines, and motors, is to evaluate the condition of the equipment to prevent and avoid mechanical failures [2]. If the results of VA are interpreted correctly and acted upon accordingly, costs associated with maintenance may be reduced. Then, the paradigm of maintenance operations can shift from a reactive approach, where repairs occur after failure, to a proactive one, using a predictive maintenance (PdM) model, in which tasks are performed when needed, and preventative methods (PM), where analysis and maintenance is scheduled, to prevent failure [3].

Though vibrations can be described in terms of displacement, velocity, and acceleration versus time, displacement and velocity are often the most important parameters to measure in machinery vibration, especially those with small clearances between machine components. Displacement can indicate imbalances in rotating machine parts, and since the largest displacements tend to occur at shaft rotational frequency, it is extremely pertinent to measure displacements of machine components due to vibrations if balancing machinery is a concern [4]. Most machines/defects generate vibrations in the range of 10Hz to 1 kHz [5], which is the frequency spectra most easily detected by vibration sensors.

There are multiple ways that sensors and software are used to measure vibrations. Generally, VA is performed using two methods: time-domain analysis, and frequency-domain analysis. Simple periodic time waveforms can be easily understood by observing time domain
representations (i.e. measurement of displacement versus time). However, vibration in large machinery involves relatively complex time waveforms, and contributions of individual machine components to the overall waveform are hard to detect. Frequency domain analysis is useful in this situation, as different components and connections tend to generate different vibration frequencies [6].

The Fast Fourier Transform (FFT) is a mathematical operation used to convert time-domain waves to the frequency domain. A Fourier series is a series of sine waves. Though overall time-domain vibration profiles can be complex, they are simply a sum of sinusoids of different amplitudes, frequencies, and phases. Fourier analysis allows for the deconstruction of complex time waveforms into individual frequency components [7]. Using FFT yields information about the frequencies at which vibrations occur and can illuminate their causes. Since it is known that different machine components and fixtures can cause vibrations at specific frequencies, spectrum analysis in VA of machines is extremely valuable.

A common problem in machine maintenance is to understand what “bad” vibration looks like. From the maintenance perspective, it is more important to determine a trend in the vibration data that points to imminent issues rather than find the vibrational limits of machinery and machine components. Generally speaking, if parts in a machine are unbalanced, misaligned, loose, eccentric, out of tolerance dimensionally, damaged, or reacting to an external force, larger vibrations will occur. Various industry and institutional standards do exist to determine acceptable and non-acceptable range of vibrations in specific machine components. However, it is impossible to fix an absolute vibration limit that would result in specific machine or mechanical component failure. Monitoring trends in vibration data over time in conjunction with comparing said data to industry standards is a good strategy to determine acceptable vibration limits on a
more individualized basis [8]. Luckily, modern VA tools, such as those developed by GTi, allow for easier interpretation of the results of such analyses.

GTi uses a combination of sensors and software packages to perform VA. Unfortunately, information pertaining to both the hardware and the software that GTi produces is proprietary, so it is more useful to discuss a general case for a VA sensor package, similar to GTi’s, which has been patented. In this case the sensing device is a ceramic piezoelectric sensor, an accelerometer to be specific. Accelerometers are full-contact transducers connected to the desired component. The accelerometer measures dynamic acceleration of a physical component and converts it to a voltage [9]. VA software identifies faults in the machinery by correlating vibration spectra of various machine components, such as a rotating drive shaft, with parameters such as maximum speed, minimum speed, and average speed of the shaft [10]. Some software packages can analyze trends over time, and even recommend specific adjustments and repairs to troubleshoot issues if distances between the sensors, shaft components, and fixtures are used as inputs. This helps maintenance teams to identify which components and systems may need monitoring and repair, and lends itself well to the PdM model.

B. Design Requirements: Vibration Analysis Device

The customer, M.C. Dean, Inc., requires a vibration analysis device that encompasses a range of features. The device must contain a variable speed motor that is at least a quarter of a horsepower. This motor must then be connected to a shaft that is capable of attaching balance rotors at any desired position. These balance rotors, which are the main mechanism for adjusting vibrations in the machine, must contain tapped holes for the attaching of trim weights. Lastly, the machine requires a protective cover that allows for access to the motor controller as
well as access to the sensor mounting pads so that the sensors can be attached to the device while the cover is attached.

C. **Scope: Shaft Alignment Device**

Shaft alignment is an area of mechanics and machines that comes in to effect when two rotating shafts need to be joined. Shaft alignment requires consideration in nearly every field from manufacturing and maintenance to the aerospace, naval engineering and automotive industries. This is evident in the fact that shaft misalignment is attributed with costing industry worldwide billions every year [11] and being the cause of half of all costs related to rotating machinery breakdowns [12].

In shaft alignment, when two shafts are in perfect alignment they are said to be collinear [13]. Collinear is defined as the center of both shafts being characterized by a single straight line [13]. In practice it is nearly impossible to achieve collinear shafts so instead one needs to define misalignment to set machine tolerances. Two types of shaft misalignments addressed in the scope of machine maintenance are parallel and angular [14]. Parallel, often referred to as offset misalignment, is when the two shaft centers are parallel but offset from each other by some distance, where offset is measured as distance from one center to the other and has the unit of mil (1 mil is equivalent to .001 in) [15]. Angular misalignment, which is when two shafts are at angle to each other [14], is measured by the difference in slopes of the two shafts and has the units of mil/in [15].

In order to grasp shaft alignment, first it is important to understand what causes misalignment to begin with. The most common cause of misalignment is called soft foot [12]. Soft foot is when the feet of a machine are not flat with its base [11]. It’s easy to picture soft foot as it is similar to when a four-legged table has a leg slightly shorter than the others; the one
short leg causes the whole table to wobble. Soft foot is the same concept except the table can be a multi-ton machine. The second greatest cause of misalignment is a bearing out of square with its housing, which is when a bearing comes out of alignment forcing the shafts to misalign [12].

With these definitions for misalignment and its causes understood, one can focus on how to fix misalignment. There are many tools for correcting misalignment, but the three most common are straightedges, dial indicators, and lasers [15]. The oldest method is using a straightedge, along with one’s eyes, to align the shafts. While this method is very simple, it provides little accuracy [12]. Another method employs dial indicators mounted to the shafts to measure offset. Dial indicators can provide high accuracy, but have low ease of use and are tough to implement [12]. The last alignment tool uses laser alignment devices which are relatively easy to use, fast, and provide very high accuracy.

Each laser alignment method begins by attaching a laser and receiver to the two shafts. The lasers then rotate around the shaft and sends the offsets and angular misalignment to a controller which interprets the data for the user. When using a laser, it is helpful to define a primary shaft, which is usually the driving shaft, and choose that as your origin [16]. Laser alignment equipment tend to have an accuracy within 1 mil offset and .1mil/in angular misalignment [17]. With advances in technology lasers alignment devices are now capable of not only measuring the misalignment, but also recommending where to place shims or implement other corrective techniques to counter said misalignment [17]. It should be noted that laser alignment devices are relatively dated as indicated by a laser alignment patent from 1994 [18]. This patent includes all the common components one should expect from a modern laser alignment device and even boasts an accuracy of 1 mil which is not much greater than modern alignment devices.
D. Design Requirements: Shaft Alignment Device

For this project, a shaft alignment training device was designed and manufactured. The device allows M.C. Dean to train its employees how to use laser alignment testing devices to find and correct shaft misalignment. This device will save M.C. Dean thousands in training costs, as well as the greatly reduced cost of the devices themselves. The shaft alignment device allows for parallel and angular misalignment as well as easy mounting of the laser tester devices.

The customer required a shaft alignment device containing a few key requirements. First and foremost, the shaft alignment sensors must be able to fit on the shafts that straddle either side of the coupler. The shafts must then be able to be offset from each other in the range of one to five hundred mils, where one mill equals a thousandth of an inch. This offset must occur both horizontally and vertically, as well as angularly. Further, the shaft must be able to rotate together while in offset.
III. Design Description: Vibration Analysis Device

A. Design Summary

Figure 1: Vibration Analysis Device

The vibration analysis device, seen in Figure 1, allows for the creation, and subsequent damping, of vibrations into the machine. By adding different weights to different locations along the radius of the balance rotors, the user of the machine can introduce imbalances that are accompanied by vibrations. These vibrations are exhibited in the bearing towers and, by attaching an accelerometer to the machine, the amplitude of these vibrations can be detected. The software embedded in the accelerometer will then tell the user where to fixture trim weights on the balance rotors in order to dampen the vibrations. After fixturing, the machine is run again
and the accelerometer will evaluate the new vibration the machine exhibits, which should now be close to perfect thus indicating a perfectly balanced machine.

B. Detailed Description

B.1: Base Plate

The base plate is crucial to manufacture precisely as it serves as the main platform for all other components. Exact dimensions were ensured by manufacturing through a CNC milling machine as opposed to manufacturing by hand. In addition, the base plate must be completely leveled and the holes precisely distanced in order for the components to sit flush. To do so, before drilling took place an indicator was used to align the placement of the holes to within three thousandths of an inch. By doing so, the indicator acts as a point of contact for each component of the device and the drilled holes are nearly completely parallel to the edge of the base plate. To account for the leveling, adjustable pegs were included to allow for the plate to sit flat on a potentially uneven surface. With the dimensioning of the base plate complete, design iterations were completed to adjust for safety and placement of other parts.

Figure 2: Base Plate
Design iterations were undertaken to comply with customer needs and the final manufacturing design for the base plate can be seen in Figure 2. Changes were made in the location of the drilled holes to create an allowance of space for the motor and motor controller to properly be seated. These changes also allow for a cover plate composed of polycarbonate to be laser cut with enough spacing as to not fracture from crack propagation which would result from holes being drilled too close. A cover that spans the width of the base plate was manufactured as a preventative safety measure in the chance that the trim weights dislodge. The design specifications of this cover tower will be explicitly described following this subsection. Also included in the final design is an array of slots in a 4x6 configuration to allow for the bearing towers to be reconfigured in different locations to test for non-linear vibration analysis. Although this form of testing is not conducted for this project, it is an extremely important factor in preventative maintenance as many machines are typically non-linear and stress on the shaft coupler is a major area of concern.

B.2: Cover

The cover's sole purpose is to ensure the safety of the users while the vibration analysis device is in use. As for design specifications, the cover allows for the attachment of the sensors onto the sensor mounting pads and allows for the motor speed controller to remain exposed so the speed of the motor can still be adjusted during trial. The final cover used for this project can be seen in Figure 3 below. As previously discussed, the use of the device includes the possibility of the trim weights detaching from the balance rotor while testing is taking place. The design process and modifications undertaken for the cover will be described below.
When selecting the material for the cover, it is important to allow the user to view the components during testing. As a result, the material selected for this project was polycarbonate. When selecting between polycarbonate and acrylic, the former was chosen due to its high impact strength, flexibility, and high transparency qualities. Acrylic is also known to crack and shatter when presented with a force due to the stiffness of the material, which would further lead to a greater safety hazard.
In comparison to the base CAD model conceived, as can be seen above in Figure 4, a few modifications have been made to the final design. Direct holes for sensor insertion may have lead to misalignment with the sensor mounting pads if placed incorrectly. This would deem the cover unusable if the sensors could not be properly mounted. Instead, slotted holes with an extra tolerance of .25 inches on each side was used to accommodate for any interference and easy fitting of the sensors.

Lastly, mounting of the cover to the base plate was done through the use of magnets instead of screws. With the initial design employing the use of L-brackets for direct mounting, this would have proved to be inconvenient when having to undo the screws to add the trim weights for trial runs. Instead, magnets were attached to the base plate and cover to securely hold the cover while testing. While magnetic sheets were extremely cost effective, the pull force was low and may have caused the cover to slip while testing. Alternatively, adhesive magnets with a max pull of 2.2 lbs are used and has proven to be sufficient in securing the cover during test trials.

B.3: Motor Support

The motor support, which consists of the back motor support and the front motor support, satisfies three requirements; mounting the motor to the device, keeping the motor stable, and ensuring alignment of the motor’s shaft along the axis of the shaft supported by the bearing towers. The back and front motor supports are similar in dimensions, although the front motor support has two additional mounting holes. Those mounting holes are located on either side of a semicircular cut-out on the face of the motor support, as illustrated below in Figure 2.
Despite the physical similarities of the front and back motor supports, the roles of the two components differ. The back motor support, seen in Figure 5, plays the role of supporting the weight of the back end of the motor. The front motor support, seen in Figure 6, has the task of supporting the weight of the front end of the motor as well as keeping the motor from rotating due to the torque it is producing. To prevent rotation from torque, the motor is mounted onto the face of the front motor support via the two mounting holes that straddle the semicircle cut-out. Together, they form a complete motor mount that can be seen below in Figure 7.
With the motor turning at speeds in excess of 5,000 RPM, intense vibrations occur throughout the supports. In order to keep the motor stable, the connections between the supports and the base plate as well as the connections between the motor and the front motor support must be extremely rigid. To ensure that these vibrations do not cause any of the connections to loosen or come undone, locknuts are used. The lock-nuts, which have a nylon ring that lines the inside of the threads, resist loosening due to vibration and ensure that the motor stays in the exact position it is clamped in so as to ensure stability and maintain alignment.

Crucial to the functionality of the testing device as a whole is the near perfect alignment between the shaft of the motor and the shaft supported by the bearing towers. While each component is dimensioned with the utmost care and precision, misalignments due to machine tool errors and human oversight are always an issue that needs to be addressed. To account for
these errors, the holes at the base of the two motor support components are slightly slotted. In doing so, the motor supports are capable of shifting along the face of the base plate and any misalignment in the horizontal position between the two shafts can be corrected. In fact, this slotting of the holes is vital in the method used to go about ensuring the components are as perfectly aligned as possible.

To align the motor supports, the bases of the supports are loosened allowing the supports to slide along the slotted holes. With the bearing towers locked in place, an extremely rigid shaft coupler, made out of a solid piece of aluminum, is then placed on the shaft supported by the bearing towers. The motor supports are then moved along the slotted holes until the shaft of the motor is aligned with the rigid coupler. Once in position, the rigid coupler is then inserted onto the shaft of the motor support, thus connecting it to the shaft of the bearing towers. Finally, the motor support bases are locked into place and the rigid coupler is replaced with the flexible coupler. The result is a motor support that provides support to the motor’s weight and torque, keeps the motor stable, and ensures near perfect alignment between the shaft of the motor and the shaft of the bearing towers.

B.4: Bearing Towers

The bearing towers, as seen in Figure 8, act as a medium for the sensor mounting pads and the sensors to be attached. To minimize the detection of the amplitudes caused by misalignment and focus on those caused by imbalance when testing, it is necessary to get the shaft holes of the bearing towers perfectly centered with the motor to not create misalignment. To do so, the towers were initially dimensioned using an edge finder to find a location to be defined as a starting point. Next, they were milled by hand until the center section of the plate were the exact same dimensions. Finally, the center holes were then drilled accounting for any
dimensional differences in the sizes of the plate so as to be perfectly aligned when attached to the base plate.

![Figure 8: Bearing Towers](image1)

![Figure 9: Mill Program for Press Fitting Bearing](image2)

The ball bearings were press fitted into the towers, as not doing so could allow for the bearing to fall loose during testing when the motor runs at higher RPM's. The hole to press fit the bearings into is created using a program on the mill, as shown Figure 8 above. The program creates a hole with a diameter of .6860 inches, which is slightly smaller than the size of the outer diameter of the bearing at .6875 inches. The bearing are then placed on top of the hole and slowly pressed into the tower using a vice.

Similar to the case of the base plate, correct alignment of the towers is extremely important. Misalignment may create unnecessary stresses on the shaft that may result in data that is not through the direct cause of mass unbalance. It also may result in a shortened life cycle of the device by causing more wear on the components.
B.5: Balance Rotors

The balance rotors play the role of introducing, and eliminating, vibrations in the device. As seen below in Figures 10 and 11 the discs contain thirty six threaded trim weight mounting holes, a flanged shaft collar, and a centered shaft hole.

These discs are made with the utmost precision. To play the role of balancing the machine, the entire disc must be completely circular, the shaft hole must be perfectly centered through the disc, and the trim weight mounting holes must be located along a consistent radial circle located at every tenth degree. Any imperfection in the dimensions of the disc will not only prevent it from acting as a machine balancing mechanism, but will also be amplified when the disc is rotated at speeds in excess of 5,000RPM.

The flanged shaft mount allows for the balance rotor to be attached to the shaft. Various flanged mounts were considered in the design, but a clamping shaft mount was selected given that it allowed for sufficient force to clamp it to the shaft without marring it. If a set screw were to be used, it would inevitably lead to permanent indents left in the shaft. While this is too minor of
defect to throw off the vibrations in the machine, it could impede the user from sliding the shaft out of the already tight fitting bearing. This would be extremely problematic as the bearing towers and the balance rotors must be capable of being fixtured in various orientations in order to evaluate different vibration scenarios.

In order to fabricate the trim weight mounting holes, the first step was to use a coaxial indicator to zero the mill on the center of the disc. Doing so allowed for the holes to be perfectly centered about the shaft hole to within a thousandth of an inch. The mill was then programmed to drill a hole along a circle located at every tenth degree. The holes were then inundated with tapping fluid and hand tapped, one by one, a process that was extremely demanding not only physically, but also mentally since proper care needed to be taken or else the tap could snap and the entire disc would need to be redone.

B.6: Shaft Assembly

![Image of shaft assembly]

**Figure 12: Shaft Assembly**

The most central component within the Vibration Analysis device is the shaft assembly because it transitions the torque and rotational motion from the motor shaft to the larger analysis shaft. It is essential for this assembly, seen in Figure 12 above, to be as aligned and accurate
as possible since the smallest difference in alignment can cause a large amount of vibration that is not due to mass imbalance. As discussed in the previous subsection, the flanged shaft collars connect the balance rotors to the analysis shaft. The shaft collars connect to the shaft by a clamping action as opposed to using a set screw. With a set screw, an indentation is left in the shaft. While this is too minor of a defect to alter the vibrations, the indent in the shaft could impede the ability of the user to slide the shaft out of the bearings. This would disallow for the reconfiguration of the components in the device and in turn render the device useless as a trainer as it would be unable to mimic different vibration scenarios seen in the field. By using a clamp style shaft collar, the shaft remains free of any marrs and the ability to reconfigure the device remains present.

The vibration analysis device requires a connection between the motor output shaft and the analysis shaft so that the movement of the motor shaft translates into the movement of the analysis shaft. These two multi-diametrical shafts must be in perfect alignment to guarantee that the vibrations created within the device are correct and measurable. To ensure this perfect alignment, a rigid coupler is first connected to the two shafts. Once connected, the bearing towers are then locked into place. The rigid coupler is then removed and replaced with the flexible coupler. Although the flexible coupler enables the motor to drive the analysis shaft in the presence of small alignment errors, it is still desired to have the shafts to be as perfectly aligned as possible. Thus, the method of using a rigid coupler first helps to minimize any misalignments and help the coupler to do as little alignment correction as possible.

The shaft assembly also consists of the ball bearings that are placed within the support towers. These bearings provide the steel shaft with the ability to spin freely within the towers, while simultaneously providing the necessary support to hold the shaft in place. It is important to select the correct bearings for this assembly because they are very difficult to replace. These
bearings are permanently lubricated and sealed, and therefore will last much longer and be much more resistance to dust and dirt that would cause exposed ball bearings to cease.

IV. Design Description: Shaft Alignment Device

Figure 13: Shaft Alignment Device

A. Design Summary

The main objective in the design and realization of the shaft alignment device is to create a device that is able to create parallel and angular offset in the shafts, with high accuracy. To accomplish this forced offset, a lead screw assembly was chosen. The lead screw assembly is able to push the towers into and out of alignment. Working backwards from the lead screw assembly the shaft alignment device design was created. The device is comprised of four subsystems as seen in Figure 13: the lead screw assembly, the baseplate assembly, the tower assembly, and the shaft assembly. The lead screw assembly is the mechanism allowing for the shaft alignment device’s alignment to be controlled. The shaft assembly provides the shafts that
will be forced into misalignment as well as mounting points for the laser alignment testers. The tower assemblies are used to mount the lead screw assemblies and provide an interface for the lead screw assembly to move the shaft assembly. Finally, the baseplate assembly is the foundation of the whole device and allows mounting points for the lead screw assembly.

B. Detailed Description (Shaft Alignment Device)

B.1: Lead Screw Assembly

The lead screw assembly is used to precisely move the shaft alignment towers in and out of alignment in both the horizontal and vertical directions. The lead screw assembly is composed of the lead screw, the lead screw nut, and turn knob. There are two sets of lead screw assemblies in the shaft alignment trainer, one assembly for the vertical movements and one for the horizontal movements. Both assemblies are identical except for a difference in length of the lead screw and lead screw nut.

Figure 14: Lead Screw Components

The lead screw assembly’s three pieces, as seen in Figure 14, provide a simple but useful mechanism for translational movement. The lead screw nut is the piece that moves the
lead screws, which in turn moves the towers. The nut is mounted to the towers or base plate side mounts by three bolts attached to the flange of the nut and bolted through the towers or side plate as seen in Figure 15. Since the nut cannot rotate due to the bolted flange, the threading of the screw through the nut forces the lead screw to move along the axial direction of the nut. This forced movement of the lead screw allows the lead screw to push against the tower or base plate which causes the movement of the tower. Finally, the turn knob of the assembly allows the user to turn the lead screw by hand. It should be noted that the turn knob is on the mounting block side of the assembly for the horizontal lead screw assemblies and on top of the tower for the vertical lead screw assemblies. This can be seen in Figure 15 with the Horizontal lead screw assembly knob being on the right and the vertical assembly knob towards the top of the figure.

Figure 15: Lead Screw Assembly Mounted to the Tower
In selecting materials for the lead screw assembly, the primary concern is the precision of the lead screw. Taking careful consideration, a ½” diameter 1018 Carbon Steel Precision lead screw is selected. This lead screw has one thread traveling the length of the rod which allows for more precision and minimal backlash with the nut. The screw also has a .1” travel distance per turn meaning it would take the lead screw 10 full rotations to travel 1”. This gives the user the ability to accurately move the lead the tower in small increments. The knob is chosen for its size and ability to mount to the lead screws. Finally, the lead screw nuts, which can be purchased, were manufactured to save about $600 in material cost. For the nuts, aluminum was selected due to its machinability, weight, and price.

The first step in mounting the lead screw assembly is to mount all the vertical nuts to the towers and horizontal nuts to the side plate ensuring that all bolts are in place and that everything is secured as shown in Figure 15. Once these pieces are securely in place, the lead screws will be threaded through the nuts until the lead screws begin to touch the baseplate and sides of the towers. Finally, all the knobs will be secured to the top of the vertical lead screw and to the side of the horizontal lead screw. Once all of the lead screw assemblies are fully mounted, the knobs will be carefully rotated until the angular and parallel misalignment in the towers is minimized to around 1 mil.

**B.2: Coupler**

In the shaft alignment device, the coupler is required to hold the shafts together as they are aligned or while in parallel or angular misalignment. The flexible coupling shown in Figure 16 is used to replicate coupling mechanisms found in machinery. Overall, the shaft and couplers are meant to serve as a small scale model of machine components that are held together by shafts, such as water pumps and motors. These machines are subject to stresses which can
cause the shafts to slowly misalign over time due to small deflections in the structures. Because the shafts are relatively rigid, flexible couplers such as the one shown in Figure 16 are often used as interfaces in these high stress, high speed environments.

The coupler consists of two hubs and a vibration-damping flexible center, shown in Figure 17. The hubs are attached to the shafts by a set screw mechanism, and the center is placed between the hubs. When the towers are moved along the base plate using the lead screw mechanisms, the center flexes to compensate for the misalignment while still holding the shafts together.
The coupler used in the shaft alignment trainer was chosen by the customer’s engineering staff, so the material choice for the coupler was mostly based upon meeting performance requirements at the lowest price possible. The hubs of the coupler are made of sintered steel with black oxide steel set screws, meant for a shaft with an outer diameter of ½”. The center is made of TPE rubber and is rated to perform at 9200 rpm with a maximum torque of 60 in-lbs. However, speed and force limitations are not the main concerns for the shaft alignment trainer. What is of main concern is the misalignment capability of the coupler. This coupler has misalignment capabilities of 0.01” and 1° in parallel and angular respectively. However, this offset is rated for being driven at full speed. Since the shaft is hand turned, the coupler can handle misalignments in excess of half an inch axially.

When the shaft alignment trainer is fully assembled, the towers must be positioned so the shafts are as close to aligned as possible. The hubs of the couplers can then be attached to the shafts using the set screws, which bite onto the shafts, and the rubber center can slide into the hubs forming the whole coupling mechanism.

B.3: Tower Assembly

The tower assemblies serve two main functions in the shaft alignment trainer. First, they act as a module to create the necessary misalignments in the shafts that will be detected by the sensors. And second, they act as a casing for the lead screw assemblies, the mechanisms which control the movement of the towers.
Each of the towers is identical and consists of two face plates, one upper top plate, two upper side plates, two lower top plates, and two lower side plates, as shown in Figures 18 and 19. Every component in the assembly is used to execute one of the main functions of the towers. The face plates, highlighted in Figure 18, rigidly hold the structure of the tower together and carry the shafts through two press-fit flanged bearings. The shafts are an integral part of the shaft alignment trainer as they are the attachment point for the sensors. The upper top plate and side plates, shown in Figure 19, function as casings and structural supports, while the lower set of top and side plates, also shown in Figure 19, are used to mount the lead screw nuts, which control the vertical and horizontal displacement of the towers on the baseplate.

The design of the towers has been modified a total of three times. Over these iterations, the tower assembly has become more modular. This has increased the manufacturability of the design and reduced possible sources of error in fit and tolerance associated with the machining processes used to realize the final product. The side plate construction, shown in Figure 19, is a
prime example of the optimization of the tower’s design over time. Initially, the plate was designed as one solid piece of thin aluminum which would be bent to fit the side contours of the face plates, as shown in Figure 20. This needlessly results in dimensioning uncertainties in the location of the drilled holes, since the position of the holes can change after the bending process. If any of the holes were drilled incorrectly, a new side plate would have to be manufactured. Due to the more modular design of the towers, the overall ease of manufacturing has been increased. Each piece of the assembly may now be manufactured and attached independently and possible errors in terms of material waste and man hours become less costly.

![Figure 20: Original Side Plate Design](image)

The materials for the tower were chosen based on their ability to support the necessary components and mechanisms of the shaft alignment trainer, while meeting budgetary restrictions. The structure of the towers is composed of a series of aluminum plates. Aluminum was chosen for its strength, durability, and weight at a reasonable price point. 3/8” thick MIC 6 aluminum alloy was selected for the face plates due to its flatness, which is desirable to facilitate proper fitting of the shafts through the towers. 1/8” thick 6061 aluminum alloy was used for the
side and top plates because of its beneficial mechanical properties and machinability at a slightly cheaper price. The towers are held together by a series of 1/4”-20 screws chosen for their relatively standard thread size. Finally, a set of flanged bearings for ½” shaft diameter and 1–3/8” housing inner diameter are press fit into the towers to support the shaft. The dimensions of the bearings were based on the shaft size, which had to fit the coupler chosen by the customer.

The towers are attached to the base plate through the lead screw assemblies. The horizontal lead screws are mounted to the side edges of the towers by the horizontal lead screw nut, then connected to the baseplate by bearings in the side mount pieces. The vertical lead screws are attached to the towers by the vertical lead screw nuts and fed through a hole in the surface of the base plate to a bearing on the underside of the baseplate. Finally, the misalignment of the shafts is manipulated by turning the knobs of the horizontal and vertical lead screws. The towers ultimately function to create the misalignments in the shafts and to rigidly support the shafts so the shaft alignment sensors can be attached.

B.4: Shaft Assembly

The shaft assembly in the shaft alignment device is used to model the misalignment of shafts in comparable machinery and machine components and to serve as an attachment point for the shaft alignment sensors. The shaft assembly is comprised of two shafts, four shaft collars, and a hand wheel, as shown in Figure 21 below.
Each shaft in the assembly is mounted through the towers using two ball bearings and held in place using shaft collars. The ball bearings allow the shaft to rotate smoothly in order to facilitate the detection of misalignments using the laser based shaft alignment sensors. The shaft collars are simply short metal tubes with set screws for clamping them into the shaft, to prevent the axial misalignment of the shafts. Though the coupler used in the shaft alignment trainer is capable of handling axial misalignments, the design requirements of the shaft alignment trainer intended it to be used for parallel and angular misalignment only. The hand wheel and ball bearings were purchased ready made. The hand wheel is used to rotate the towers when the shaft alignment sensors are attached to the shafts. In designing the lead screw assembly, the components were all chosen to best meet the design requirements at the cheapest possible price.
Materials for the shaft assembly were chosen based on their ability to accurately model shaft misalignment in machinery as well as meet the design requirements for the shaft alignment trainer. A 1566 carbon steel rotary shaft was picked due to its strength and price. Carbon steel rotary shafts, also called drive shafts, are often used with gears, sprockets, rotary bearings, and other power transmission components, and so provides a good reference for the types of shafts the sensors will be used on in practice. A 6061 aluminum rod was chosen for the shaft collars, due to its abundance and low cost. Finally, a zinc hand wheel was chosen due to its low cost. The only requirement for the hand wheel was for it to have an unthreaded hole and a set screw to attach it to the shaft. Because the shaft assembly is an essential subsystem of the shaft alignment device, its proper integration into the finished product is of utmost importance.

Extreme care was taken when machining the towers to assure that the shafts are as close to perfectly aligned as possible when the towers are in their neutral position. To that end, the holes in the faceplates of the towers into which the bearings were press fit were all clamped together when they were machined. This facilitated proper fitting of the shaft assembly in terms of its natural alignment. The shaft assembly is the final subsystem to be integrated into the design, as it cannot be properly attached until the other subsystems are complete. The chamfered shafts are pushed through a ball bearing, then fitted with the collars, and then pushed through the other ball bearing, as seen in Figure 22. When the shafts are set in the middle with the coupler, the shaft collars are locked onto the shaft using set screws, to prevent axial misalignment. Finally, the hand wheel is attached with a set screw so that the shaft can be rotated.
B.5. Base Plate

The base plate is made of 11.7”x 23” highly machinable ½ inch thick MIC6 aluminum. The purpose of the base plate is to support the bearing towers, the side mounting blocks and to hold the adjustable feet. The positions of the holes were carefully studied and precisely determined in the CAD assembly process and were then milled using the CNC milling machine. The methodology to carry out precise manufacturing of the holes is mentioned in section III.B.1. At the four corners of the base plate, holes were drilled and tapped to connect to the adjustable feet. Adjusting the height of the feet allows the technician to ensure the surface of the base plate is parallel to the table’s surface. Quarter inch holes line the sides of the base plate, acting as a fixturing point for the side mounting blocks. Originally, four pairs of ½ inch diameter holes at the central areas of the left and right halves of the base plate allow for the lead screws to pass through. Afterwards, the design was changed and these eight holes were filled with aluminum cylinders which have ½ inches in diameter and 0.5 inches in length. Two aluminum
sheets are fixed at the bottom of the base plate using bolts in order to add extra strength to the base plate’s structure.

![Figure 23: Shaft Alignment Device Base Plate](image)

V. Evaluation and Testing: Vibration Analysis Device

A. Summary

The vibration analysis tool is complemented by an accelerometer and a vibration analysis software installed on a portable device, such as an iPad. This vibration analysis tool mainly detects and corrects the vibration due to machine imbalance. By attaching the accelerometer to the magnetic sensor mounting pads on the bearing towers and running the software, the technician can obtain the vibration signal from the rotating machine and hence determine the solution to correct the machine imbalance.

B. Detailed Description
A balance rotor, seen again in Figure 24, is used to balance the machine. Figure 24 shows the front view of the balance rotor which has thirty six holes on its rim with each hole located 10 degrees apart from the next. As discussed previously, the balance rotor is fixed onto the shaft using set screws and its position along the shaft can be adjusted. Trim weights will be added around the circumference of the balance rotor onto the specific holes to counteract the unbalanced forces caused by heavy spots as specified by the software to put the machine in balance.

An accelerometer will be used to obtain the vibration signal of the towers. It is attached to the sensor mounting pads located on the sides and top of the towers. The sources of vibration have unique time waveforms which display signals with amplitudes on a time series. The waveform of each vibration signal superimposes and produces a composite waveform and this waveform can be isolated and separated by Fast Fourier Transformation (FFT) built into the vibration analysis software to obtain simplified individual signals. In the FFT spectrums, the vibration amplitude of the machine is plotted against the frequency (Hertz). After an initial,
unbalanced run of the machine at the customer’s headquarters, the FFT was found. Using the software, the technician was then able to zoom in on the FFT and evaluate it. A screenshot of the FFT found is seen below in Figure 25.

![FFT of Unbalanced Vibration Analysis Device](image)

**Figure 25: FFT of Unbalanced Vibration Analysis Device**

Repeatability is essential to the testing and analysis of vibrations in the machine. When the machine’s performance is tested, it is important to ensure that the machine operates at the same state during each test because the vibration differs when the speed and load change. The first step to test the machine is to set the motor at a certain speed (RPM) on the motor controller and obtain the original vibration amplitude of the unloaded machine using the software. Next, a trial weight is added on the balance rotor at the zero degree mark. The machine is operated at the same speed and run again and the software marks the vibration amplitude of the machine with the trial weight at the zeroth degree location. Then, the trial weight’s position on the balance rotor is changed to three other positions, for example at 100 degrees, 180 degrees and 210 degrees. Maintaining the same motor speed, the vibration amplitudes of the machine are
marked respectively. The technician then enter the mass of the trim weight used into the software and the software then calculates the position and weight in which a mass should be added to the balance rotor to counteract the imbalance. Lastly, the trim weight is fixed onto the balance rotor at the location specified by the software and the vibration amplitude can be reduced when the machine is operated. The desired vibration amplitude should be 0g.

Additionally, the software is capable of displaying the spectrum of vibration signals, helping the staff to understand the performance of the machine. The staff can identify vibration peaks and relate to a source component on the machine and then search for the similar patterns in the data according to the existed vibration rules for machine fault. A machine’s rotational speed is the standard frequency and is referred as 1X frequency. The vibration that has a 1X frequency or occurs at a whole multiple of 1X frequency is the synchronous vibration. The vibration that is greater than the 1X frequency but is an integer multiple of it is the non-synchronous vibration [19].

Measuring the amplitude of the vibration peaks can determine the severity of the fault. Upon testing at the customers headquarters, the device was found to not only produce an imbalance, but correct it as well. The sensor fit perfectly onto the device, as seen in Figure 26 below.
VI. Evaluation and Testing: Shaft Alignment Device

A. Summary

The testing of the shaft alignment is done using a laser alignment tester and the accompanying GTI software. The two sensors are mounted to the two shafts, aligned, and rotated. The laser device then measures offset in a 2D plane at each 90° position around the shaft. Once this data is collected the shaft alignment software is used to interpolate the data points to provide the technician with the offset of the shafts. The technician can then use the software to make the appropriate changes to put the devices into alignment.
B. Detailed Description

The first step in testing the shaft alignment is to mount the laser tester devices to the shaft on opposing sides of the coupler, as seen in Figure 27. Once the devices are mounted, the technician adjusts the devices until the sensors are in alignment with each other, a process shown in the screenshot seen in Figure 28 below. Once the devices are in relative alignment with each other, an initial reading is taken. The shaft is then rotated 90° using the attached handle and a second reading is taken. This process of taking measurements at each
interval of 90°s is repeated until a full rotation is completed. The shaft alignment software can then interpolate this data and can give a highly accurate reading of the shafts offset. This reading is within 1 mil (.001 in) of true alignment.

![Figure 28: GTI Shaft Alignment Software Screenshot](image)

With the angular and parallel offsets found, the technician can input the distance from the shaft to the mounting points of the tower. With this data, the software will inform the technician how much each mounting point needs to be adjusted in order to achieve shaft alignment. The technician then uses these values along with the known value of one rotation of the lead screw for .1” travel. Once each lead screw has been rotated to its desired position offset readings can be redone to find the new offset. The user can then repeat the tower movement and offset readings as necessary until the offset is within the acceptable limits for the machine.

**VII. Summary and Recommendations**
In completing these designs, all of the customer’s design requirements were fulfilled. A table summarizing the design requirements of each training device and the completion status of each requirement is given in Table 1 and Table 2 for the vibrational analysis and shaft alignment training devices, respectively.

### Table 1: Vibrational Analysis Device Design Requirements Status

<table>
<thead>
<tr>
<th>Design Requirements</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor: Variable speeds (Max RPM: 3400), ¼ HP or greater, speed controller</td>
<td>Achieved</td>
</tr>
<tr>
<td>Balance Rotor: Adjustable position along shaft, attachable trim weights</td>
<td>Achieved</td>
</tr>
<tr>
<td>Cover: Slots for sensor insertion, speed controller remains exposed</td>
<td>Achieved</td>
</tr>
<tr>
<td>Adjustable Feet for leveling on base</td>
<td>Achieved</td>
</tr>
</tbody>
</table>

### Table 2: Shaft Alignment Device Design Requirements Status

<table>
<thead>
<tr>
<th>Design Requirements</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allow Shaft Alignment sensors to fit</td>
<td>Achieved</td>
</tr>
<tr>
<td>Shafts rotate in offset</td>
<td>Achieved</td>
</tr>
<tr>
<td>Adjustable feet for leveling base</td>
<td>Achieved</td>
</tr>
<tr>
<td>Vertical and Horizontal offset of shafts: 1-500 mils (1 mil = 0.001 in)</td>
<td>Achieved</td>
</tr>
<tr>
<td>Angular offset: 1-500 mills/in</td>
<td>Achieved</td>
</tr>
</tbody>
</table>

All requirements were met upon completion of the manufacturing of both devices. For the vibrational analysis trainer, the purchased motor was ¼ HP, included a speed controller, and can achieve a maximum rotational speed of 5400 RPM. The adjustable position of the balance rotors was accomplished by designing and manufacturing a base plate with an array of holes for
the mounting of the bearing towers onto which the shaft and balance rotors are mounted. The balance rotors include tapped holes along the rim for the attachment of trim weights. A set of polycarbonate pieces were laser cut to assemble the cover with a set of slots to allow access to the motor, the shaft, and sensor mounting pads when the machine is running. Finally, a set of threaded feet were attached to tapped holes in the base plate. The running speed of the motor was verified using a tachometer and an accelerometer based vibration sensor at M.C. Dean’s facilities at the Mark Center in Arlington, VA.

For the shaft alignment trainer, the manufacturing accomplishments included the design and machining of the towers to allow for rotation of the shafts in offset. The same set of threaded feet were selected for the shaft alignment training device and screwed into a set of legs that were machined from aluminum rods on the lathe. As with the vibration analysis training device, a number of the design accomplishments were validated through testing at M.C. Dean’s facilities at the Mark Center. These accomplishments include verifying the sensors fit and are able to rotate around while remaining clamped to the shaft and the ability of the lead screw mechanisms to produce parallel offsets of 1-500 mils and angular offsets of 1-500 mils/in, which can be seen in Figures 27 and 28.

Furthermore, the two devices were completed within the budgetary restriction given by the customer. In fact, the overall cost of the project was considerably lower than the budget allotted. The overall cost of the two devices tallies to $2,225.45. With an initial budget of $3,000, the project was able to be completed about $775 under budget. This is even more impressive when you consider the fact that the customer could have purchased these devices from a third party for around $6,000. If the $600 that was allotted by the school is subtracted from the overall cost, our team was able to save the customer over $3,100.
Though the requirements of this project were met upon the completion of the manufacturing of both devices and verification of their functionality through integration and testing, the following recommendations might improve future designs, processes and projects with a similar scope.

Over the course of the design and realization of the vibrational analysis and shaft alignment training devices, a number of technical designs, designs for manufacturing, CAD, precision and CNC machining techniques and processes were employed to manufacturing the final products. The initial stages involved spending a large portion of time on the conceptual design of the mechanical subsystems and the CAD of the two training devices. The CAD assemblies went through a number of iterations before machining began. Once the manufacturing of the devices was started, less focus was placed on updating the CAD models, meaning a large investment of time and resources in keeping accurate technical drawings throughout the machining process. It seems more advantageous to maintain an up-to-date CAD model of the entire assembly so that the design and manufacturing challenges can be tackled before they arise rather than after they are met. Additionally, or alternatively, an overall increase in devoting time and resources to conceptual design and CAD may benefit in this scenario as to leave more time for evaluation before machining operations begin. Perhaps assigning an individual or sub-team to solely work on these aspects of the product could be another way to accomplish the various design and manufacturing goals.

A number of tactics could also be employed to improve the project’s management. There were many instances both during the design and manufacturing phases of the project where there was not enough diversity in tasks and available equipment to put each team member’s time to use effectively. In many fields of engineering, project schedules are often assigned to a specific individual or team. To improve the integration of the final product as well as the
subsystems and sub-teams, it could be pertinent to assign the role of schedule development and management to a specific team member or group. Such a role might also entail optimizing the division of labor amongst the project team. For example, it could be useful to have one sub-team primarily focus on the design phase, and take a secondary role in the manufacturing, while the manufacturing team takes on a larger workload while taking a less intensive role in other phases of the project, by focusing on research, presentations, budgeting and correspondence with the customer. A dedicated schedule manager could also keep better track of hours and even manage the budget or perform other administrative tasks throughout the life-cycle of the project.

Other recommendations to improve the management and realization of the project include beginning the testing process earlier, keeping better track of the time allocated to each phase of the project, and improve the synergy to better allocate team resources. Earlier testing leaves more time for design optimization and troubleshooting on the back end of the process. This could be accomplished by reducing the team size and project scope slightly. For example, it may be better to have a team of four to five members work on one device rather than six working on two devices.

Overall, while this project involved a steep learning curve in the design, manufacturing, and management of each subsystem and their integration and testing, the recommendations presented here could benefit similar projects undertaken in both the manufacturing and operations and maintenance fields. Going forward, the process plans, technical drawings, CAD models, material procurement and order forms, and budgetary spreadsheets kept and recorded over the life-cycle of this project, as well as the technical literature reviews, design descriptions, evaluation and testing methods, and recommendations presented in this report provide a helpful
framework for future work in applications of the design and manufacturing of precision and verification equipment and devices for use in machinery maintenance.
VIII. References


