Design and Construction of Vibration Test Stand

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Abstract

A team of four mechanical engineering students has developed a vibration test stand as an engineering capstone project. The goal was to design and construct an educational tool that will allow engineering students to better understand vibration phenomena associated with the normal operation of various machinery and common machinery faults. This educational tool must be able to simulate, measure, and analyze vibration phenomena.

The vibration test stand was divided into two subsystems: vibration simulator and vibration analyzer. The vibration simulator is a mechanical system consisting of a motor and rotors with various interchangeable components. The simulator was designed to produce the following vibration phenomena: imbalance, misalignment, flow-induced vibration, and impact loading. The vibration analyzer is a system of accelerometers, data acquisition devices, virtual instruments, and a device/user interface used to display vibration data and control the analyzer. The vibration analysis tools to be implemented included frequency spectrums and acceleration waveforms. Portability, ease of use and setup, and safety were all factors considered during the design of the device.

Introduction

The objective of this project is to design and construct an educational tool that will allow engineering students to better understand the applications and importance of vibration analysis in industry. Vibration analysis is an important tool used in condition monitoring. Condition monitoring is used to identify problems in machinery before failures occur, thereby extending machine life and reducing the waste and cost incorporated with broken machinery and downtime. Vibration analysis can be considered a practice that promotes sustainability because reduction of waste and cost can be directly related to it.

The vibration test stand designed for this project will simulate vibration phenomena associated with the normal operation of various machinery and common machinery faults. The test stand is divided into two functional systems, the vibration simulator and the vibration analyzer as shown in Figure 1. The vibration simulator is the mechanical device used to create vibration phenomena associated with misalignment, imbalance, impact loading, and flow-induced vibrations. The vibration analyzer is a system of transducers, data acquisition hardware, and data processing hardware that is used to acquire and process acceleration waveform and motor speed.
The vibration test stand is being designed and constructed by four mechanical engineering students. Two students are primarily designing and constructing the vibration simulator. The other two students are primarily designing the vibration analyzer.

**Capabilities**

To better define the functions of the vibration test stand, the following capabilities were identified:

- The vibration test stand must be able to demonstrate vibration phenomena associated with the following common machine faults:
  - Rotating imbalance
  - Shaft misalignment
    - Parallel
    - Angular
    - Parallel and angular combined
  - Impact and slider crank vibration
  - Flow-induced vibration
- The vibration test stand must be able to demonstrate vibration phenomena associated with normal machine operation (i.e. healthy operation).
- The vibration test stand must be able to collect, process, and display vibration data.
- The vibration test stand must be able to display vibration data in both the time domain and frequency domain.
The vibration test stand is to be used as a lab tool and should conform to a “table top” layout.

Requirements

To fulfill the desired capabilities, the following design requirements were determined:

- The vibration test stand should fit and fully operate on a table top.
- The vibration test stand should be easily assembled and disassembled.
- The vibration test stand must be able to change between functional configurations within a time of 10 minutes.
- The vibration test stand must not weigh more than 70 lb to maintain portability.
- The vibration test stand must be powered by standard 120V AC. Accelerometer power supplies will be powered by 9V batteries.
- The vibration test stand must be operable at various speeds and the operating speed must be monitored by a tachometer.

Viable Designs

Three viable designs were considered for both the vibration simulator and the vibration analyzer. Variations in the vibration simulator designs included component choice and component layout. Variations in the vibration analyzer designs included the number and type of accelerometers, necessary power supplies and type of data acquisition hardware. Pugh’s Method was used to determine the best design for each system.

Pugh’s Method is a design selection strategy which compares characteristics of competing designs. The first step in Pugh’s Method is to determine all characteristics relevant to fulfilling the purpose and desired abilities of the design. One of the competing designs is then selected as a reference and the characteristics of all other designs are compared to this reference. If a design’s specific characteristic is considered less desirable than the reference then the design receives a score of -1 for that characteristic. If a design’s characteristic is considered more desirable than the reference then the design receives a score of +1 for that characteristic. The design with the greatest total score is considered to be the best design.

Vibration Simulator – Viable Designs

The first vibration simulator will include a motor coupled to one of three shafts. The first shaft will be used to simulate imbalance. It will have an inertial disk with threaded holes located radially around the shaft so that various degrees of imbalance can be represented. This shaft will also be used to transmit power to a fan, to demonstrate flow-induced vibration. The second shaft will be used to simulate the inertial loading of a slider crank. The third shaft will simulate three types of shaft misalignment: axial, angular, and a combination of the two. For each condition the
Vibrations will be measured and the frequency spectrum will be found and recorded using a LabVIEW virtual instrument.

The second design of the vibration simulator is similar to the first design in every aspect except flow-induced vibration will be demonstrated by a centrifugal water pump instead of a fan. The third design of the vibration simulator is similar to the first design except the number of shafts is reduced from three to two. One shaft will be used to demonstrate rotating imbalance, slider-crank, and flow-induced vibrations and the second shaft will be used to demonstrate shaft misalignment.

The three vibration simulator designs were evaluated on five characteristics: weight, cost, safety, motor placement, and portability. A better design was considered to have lower weight, lower cost, higher safety, fewer motor positions, and more portability. The best design was found to be Design #3. Full results of the evaluation are in Table 1.

<table>
<thead>
<tr>
<th>Engineering Characteristics and Customer Requirements</th>
<th>Design Option 1</th>
<th>Design Option 2</th>
<th>Design Option 3</th>
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<td>Weight</td>
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<td>+</td>
</tr>
<tr>
<td>Cost</td>
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<td>●</td>
<td>+</td>
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<tr>
<td>Safety</td>
<td>S</td>
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- Reference (value = 0)
- Less desirable than reference (value = -1)
+ More desirable than reference (value = 1)
S Equally desirable to reference (value = 0)

**Vibration Analyzer – Viable Designs**

The first vibration analyzer design consists of two tri-axis accelerometers, each requiring a dedicated power supply. The accelerometers will be equipped with magnets for mounting to test stand components. The National Instruments data acquisition module for these accelerometers will be a 16-bit analog input module (NI 9215). This module has pin connections and will not provide excitation voltage to the accelerometers.

The second design of the vibration analyzer consists of one tri-axis accelerometer equipped with a magnet for mounting to test stand components. The National Instruments data acquisition
module for this accelerometer will be a module specified for accelerometers, NI 9233. The NI 9233 uses bulkhead connectors and provides excitation voltage for the accelerometer, eliminating the need for a dedicated accelerometer power supply.

The third design consists of two single axis accelerometers, each requiring a dedicated power supply. The accelerometers will be equipped with magnets for mounting to test stand components. The National Instruments data acquisition module for these accelerometers will be a 16-bit analog input module (NI 9215). This module has pin connections and will not provide excitation voltage to the accelerometers.

The three vibration analyzer designs were evaluated on three characteristics: cost, number of accelerometer axes, and complexity. A better design was considered to have lower cost, lower complexity, and a greater number of axes. The best design was found to be Design #3. Full results of the evaluation are in Table 2.

<table>
<thead>
<tr>
<th>Engineering Characteristics and Customer Requirements</th>
<th>Design Option 1</th>
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<th>Design Option 3</th>
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</table>

● Reference (value = 0)
- Less desirable than reference (value = -1)
+ More desirable than reference (value = 1)
S Equally desirable to reference (value = 0)

Vibration Simulator – Proposed Design

The proposed design of the vibration test stand compromises of vibration simulator design #3 and vibration analyzer design #3. The design of the vibration simulator will include a motor coupled to one of two shafts. One shaft will be used in three different configurations. The first configuration will have inertial disks with threaded holes located on a bolt circle around the shaft so that various degrees of imbalance can be demonstrated (Figure 2). The next configuration will transmit power to a fan to demonstrate a flow-induced vibration (Figure 3). The fan will have a removable partial louver to cause resistance against the fan blades. Fan blade resistance will demonstrate a vibration phenomenon known as vane pass vibration. The third configuration will be used to simulate the inertial loading of a slider-crank (Figure 4). This configuration consists of a crank mounted to the end of the shaft, slider, and spring.
Figure 2: Vibration Simulator Imbalance Configuration

Both shafts are ½” diameter steel and are coupled to the motor with a flexible spider coupling. The spider coupling was chosen so that vibrations from the motor would be dampened and it provides for quick change over between configurations. The imbalance, slider-crank, and flow-induced vibration configurations use self-aligning ball bearings. Self-aligning ball bearings were chosen to compensate for misalignment. The imbalance configuration uses two inertial disks which can be located at any position between the bearings. The inertial disks have eight ½” tapped holes on a 2” bolt circle into which ½” set screws may be threaded. These set screws are used as imbalance masses. The different types of imbalance can be achieved through the location of the inertial disks on the shaft and the location of the set screws on the disks.
The flow-induced vibration configuration (Fig. 3) uses a 6” diameter 4-blade fan which produces a flowrate of 320 cfm at 4200 rpm\textsuperscript{1}. The fan will not operate at rated speed, but at the maximum speed of the motor (1800 rpm). A four blade fan was chosen because the vane pass vibration phenomenon occurs at a frequency equal to the product of the shaft frequency and number of vanes of the rotating element. Using a fan with few blades lessens the need for an extremely high sampling rate for accelerometers, data acquisition hardware, and data processors. Because the fan requires a 3/16” shaft attachment, a removable ½” to 3/16” adapter was designed to attach to the end of the main driving shaft. The fan is covered in a protective shroud to prevent user injury. A removable partial louver was designed to cover the lower half of the fan outlet. The partial louver will cause resistance on the fan blades and thereby increase the magnitude of the vane pass vibration.
The slider-crank configuration (Fig. 4) consists of a crank, coupler, slider, mounting block, and bronze bushings. The crank has a 2” stroke-length, the coupler is 3.25” from pin-to-pin, and the slider is 7.125” from pin-to-end. Bronze bearing inserts were used for the pin-joints and sliding joint. A clevis rod end was used to connect the slider to the coupler.
The misalignment configuration (Fig. 5) consists of two shafts connected by a helical beam shaft coupling, one permanent bearing block, one interchangeable bearing block (four options), and radial ball bearings. The helical beam shaft coupling was chosen because it allows for 10° of angular misalignment and 0.04” of parallel misalignment between shafts. Misalignment is to be simulated through the use of four different bearing blocks. Each block is designed to simulate one of the following phenomena: parallel misalignment, angular misalignment, parallel and angular misalignment, and no misalignment. The blocks were designed to utilize 50% of the angular misalignment tolerance and 100% of the parallel misalignment tolerance of the coupling.

The motor used to drive the vibration simulator was chosen based on requirements of the system and requirements of other simulator components. The motor was required to be variable speed (100-1800 rpm), be powered by 120V AC, and provide a minimum torque of 0.5 lb-ft. The minimum torque was determined by finding the maximum torque required by the vibration simulator. The maximum torque was equivalent to the sum of the maximum torque required by the slider-crank and the rolling resistance of the self-aligning bearings. The maximum torque of the slider-crank was found through calculation and the rolling resistance of the bearings was found through measurement.

The motor chosen for the vibration simulator was a 0.25 hp Marathon microMAX™ AC Inverter Duty Motor. An inverter duty motor was chosen to prevent overheating at low operating speeds. The motor requires 230V three phase input which will be provided by a three phase variable frequency drive which requires 120V single phase input. The variable frequency drive will be used to vary the speed of the motor.
Vibration Analyzer – Proposed Design

The vibration analyzer design consists of two single axis accelerometers, each requiring a dedicated power supply. The accelerometers chosen for the vibration analyzer are PCB Piezotronics industrial grade accelerometers. These accelerometers are integrated circuit piezoelectric accelerometers and are capable of measuring a range from 1 to 10,000 Hz. The accelerometers will be equipped with magnets for mounting to test stand components. The accelerometers are powered with a 9 volt battery powered signal conditioner.

A proximity sensor was chosen to serve as the tachometer. It was chosen because it was a non-obstructive way of measuring the motor speed.

The National Instruments data acquisition module chosen for the vibration analyzer is the 16-bit analog input module. The carrier chosen for the data acquisition module is Hi-Speed USB Carrier. The module and carrier provide communication between the transducers and the data processor.

The data processor and user interface is a LabVIEW Virtual Instrument. The virtual instrument allows the user to select the sampling rate of the data acquisition hardware and the period to examine acceleration data. Based on voltage input from the data acquisition hardware the data processor calculates motor speed and converts the acceleration data from time domain to frequency domain.

Motor speed is calculated by comparing the voltage output from the proximity sensor to a threshold voltage. Digital logic is used to determine the number of voltage spikes per sampling period. This data is then converted to revolutions per minutes. Acceleration data was converted from time domain to frequency domain using a Hanning Digital Fourier Transform. The amplitude of the acceleration in frequency domain is the root mean square of the acceleration in the time domain.

The virtual instrument front panel, shown in Figure 6, consists of acceleration waveforms and frequency spectrums, tachometer display, knobs for period and sampling rate adjustment, data export option, and an on/off switch.
Validation

System testing was conducted after the completion of the vibration analyzer and the rotating imbalance portion of the vibration simulator. A photograph of the vibration simulator in the rotating imbalance configuration is shown in Figure 7. A set screw was placed in each inertial disk in identical positions. The disks were placed so that there was equal distance between the bearings and disks. The simulator was set to run at full operating speed of 1800 rpm (30 Hz). The tachometer displayed a rotational speed that varied between 1750 rpm and 1800 rpm. An accelerometer was placed on top of each bearing to measure vibration in the vertical direction. The acceleration waveform and frequency spectrum were similar for each. As expected, a large acceleration was detected at running speed (30 Hz), as shown in Figure 9.
Future Work

Proposed additions to the vibration test stand include the installation of a centrifugal pump, order tracking filter, and modal analysis option. The inclusion of a centrifugal pump will be used to demonstrate the vibration phenomena associated with cavitation. Vibration caused by cavitation is non-synchronous and has a “raised floor,” meaning that the vibration frequency spectrum will not return to a near zero value over a range of frequencies. Non-synchronous vibration occurs at frequencies which are not multiples of the operating speed of the machine. These multiples of operating speed are also called orders.

An order tracking filter eliminates vibrations which occur between multiples of the operating speed which will allow users to more easily identify synchronous vibrations. The inclusion of a modal analysis function, which uses an impulse mallet, will allow students to measure the natural frequencies of static elements.

Conclusion

The objective of this project is to design an educational tool that will allow engineering students to better understand vibration phenomena associated with the normal operation of various machinery and common machinery faults. Students will use acceleration waveforms and frequency spectrums to observe shaft misalignment, imbalance, impact loading, and flow induced vibrations. The vibration test stand will teach students the use of vibration analysis as a
condition monitoring tool. Condition monitoring is a common practice in industry and is a crucial part to improving machine health. This vibration test stand demonstrates the industrial application of engineering principles.

The vibration test stand is divided into two functional subsystems, the vibration simulator and the vibration analyzer. The vibration simulator is a mechanical system that will demonstrate vibration phenomena and the analyzer is a system of accelerometers, data acquisition hardware, and data processing software. The division of the vibration test stand allows it to be priced as two separate systems.

References


