AC 2010-798: MASS UNBALANCE IN AN MET COURSE

Nancy Denton, Purdue University

Nancy L. Denton, PE, CVA III, is a professor and the associate department head for the Purdue University MET Department. Her educational endeavors focus on awareness and inclusion in STEM and experimental mechanics, while her research interests include applications of machinery monitoring and data acquisition. She is active in ASEE and serves as the Academic Director for the Vibration Institute.

Marc Williams, Purdue University

Marc E. Williams does contract work in the field of vibration analysis. He has extensive experience with rotating and reciprocating equipment in the Power, Paper, Steel and Food Processing Industries. Williams holds an M. S. in Mechanical Engineering Technology from Purdue University and is certified as a Vibration Analyst Category III from the Vibration Institute.

Joseph Kmec, Purdue University

Joseph F. Kmec is currently Associate Professor in Mechanical Engineering Technology at Purdue University, West Lafayette, IN. His teaching areas of concentration are energy-based and include Applied Thermodynamics, Internal Combustion Engines, Motorsports, and Power Plant Systems. His recent activities involving student projects include engine simulation, power plant performance analysis, and nuclear technology. He may be reached at: kmecjf@purdue.edu.

Mass Unbalance in an MET Course

Abstract

Mass unbalance, the condition where the centers of mass and rotation differ, is one of the most common sources of vibration in rotating machinery. Mechanical Engineering Technology (MET) students are likely to encounter vibration throughout their careers and need to understand its generation, transmission, and testing. Conveying vibration concepts effectively to students who typically have only limited exposure to differential equations presents a challenge for engineering technology faculty. Mass unbalance and related corrective procedures offer a practical venue for communicating fundamental vibration concepts, design concerns, experimental techniques, data analysis, and dynamic balancing methods to engineering technology students. The purpose of this paper is to document the versatility of mass unbalance and balancing as an instructional aid in an upper division elective course in machinery health monitoring. Examples of student assignments incorporating mass unbalance are presented. Results of ongoing assessment of related course learning objectives are provided.

Technical Background

Working from theory for a simple single degree of freedom vibrating system undergoing forced vibration, the force due to a rotating mass unbalance is the product of the eccentric mass, m, and its rotational acceleration component, $e\omega_f^2$, where e is the offset distance from the center of rotation to the eccentric mass and ω_f is the rotor's rotational speed in units of radians per second. The resulting applied force is modeled as $F(t) = (me\omega_f^2)\sin(\omega_f t)$.[1] Experimental data verifies the vibration energy caused by mass unbalance is essentially all included in a single sine wave at the frequency corresponding to operating speed.

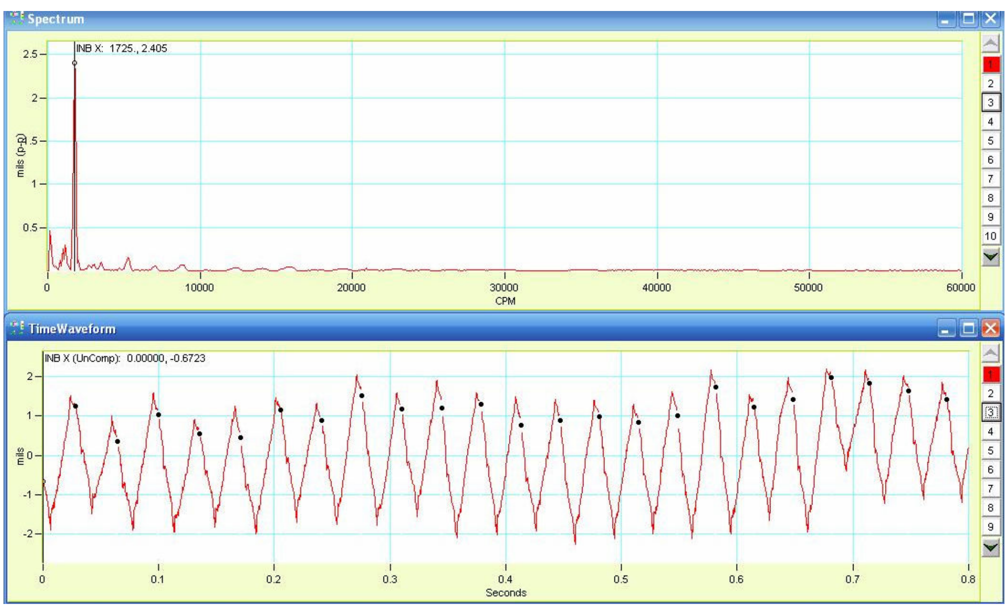

Figure 1. Typical unbalance condition

Awareness of the existence of mass unbalance dates back at least several centuries.[2] As machinery operating speeds have increased, understanding the force that mass unbalance causes and reducing that force have become critical. Measuring this force directly is not possible, however. Vibration vector-based balancing procedures instead work to identify the relationship between the magnitude and phase of the vibration vector caused by mass unbalance and the magnitude and phase of the corresponding force vector. These procedures rely on an iterative process where a known mass is added at one or more known locations and the rotor operates at a constant speed. Working from the resulting vibration vector(s), the measured vibration vectors can be used to determine the mass needed to cancel out the effects of the existing mass unbalance and where it should be located. The process was originally developed graphically, as the single-plane balance plot example in figure 2 shows.[2-4] Balancing software is typically used to accomplish the balancing process now, but is not set up to handle all possible phase angles or operating speeds that fall above the first critical speed, where the lag from force to displacement shifts from nearly in phase to nearly out of phase and the location of the correction mass must shift accordingly.

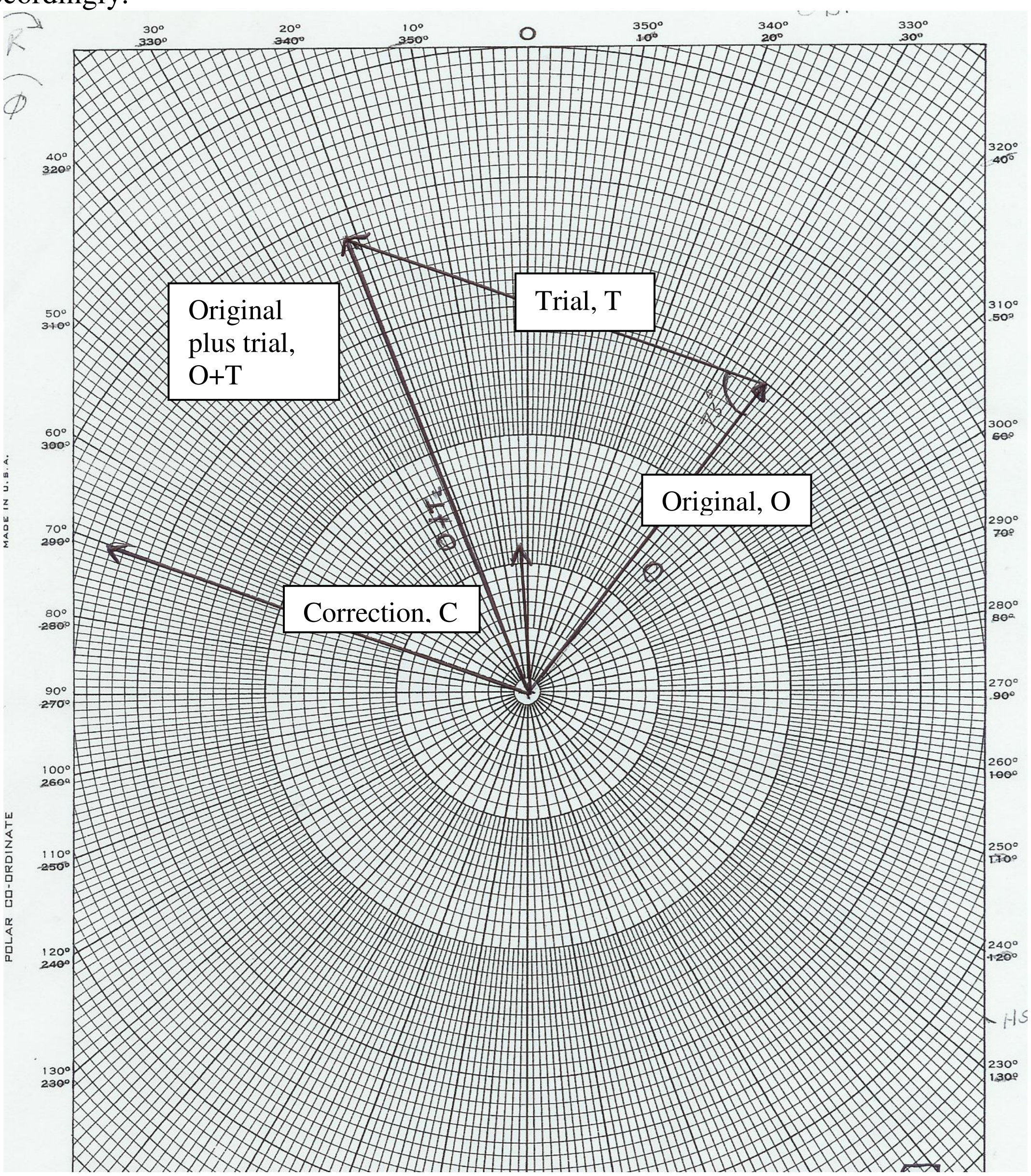

Figure 2. Example of Polar Plot for a Single Plane Balance

Mass Unbalance in a Machinery Health Monitoring course

Theoretical vibration concepts, experimental techniques, order analysis and balancing procedures all find a place in a single upper division MET elective course. MET 31700 Machine Diagnostics is a three-credit semester course that meets for two 50-minute lectures and one 110-minute laboratory session per week. The course topics begin with theoretical vibration of single degree of freedom systems.[5] Experimental work is tied closely to theory whenever possible. Time and frequency domain relationships are repeatedly noted, setting the foundation for analyzing vibration signals for diagnostic purposes. Phases are explored with respect to vibration vectors and critical speeds. Corrective action via single and dual plane balancing is practiced. Relevant experimental work includes measuring rotational speed, approximate natural frequencies, critical speeds, and if available, correlation of vibration trends, spectrum, and time-wave form collected during monthly predictive maintenance data collection. Correlation of this data that may be due to process changes such as changes in gas/liquid/solid properties being processed or equipment wear over time, e.g., mechanical wear, looseness, bearings, structure, provides insight into equipment condition and its eventual failure. The latter introduces students to machinery condition monitoring, an industrial practice that ensures that potential equipment failure is detected[6]. Mass unbalance serves as a venue for introduction of numerous course topics, and is the primary focus for two lecture and two laboratory sessions.

The first use of mass unbalance comes selecting appropriate isolation via experimental work. Mass unbalance provides a known force for a simple two-section test stand with an enclosed electric motor top section and a base. A small disk with a given eccentric mass added to it is attached to the motor's rotor, as shown in figure 3. Students learn to test for approximate natural frequency of the top section via a bump test, then measure the displacement transmitted to the base. Several sets of elastomeric pads and metal springs are installed between top and base, one set at a time. Each mounting change causes a shift in the system's stiffness and natural frequency. In contrast to their intuitive understanding of vibration, the students demonstrate that the relationship between forcing frequency and natural frequency is key to determining if an isolator will reduce or amplify transmitted vibration force and displacement. Data reduction includes determining the amplitude of the mass unbalance force, calculating the frequency ratio and system stiffness from measured values, considering the dimensionless magnification factor and transmissibility ratio, and finding the force transmitted from the motor to its base.

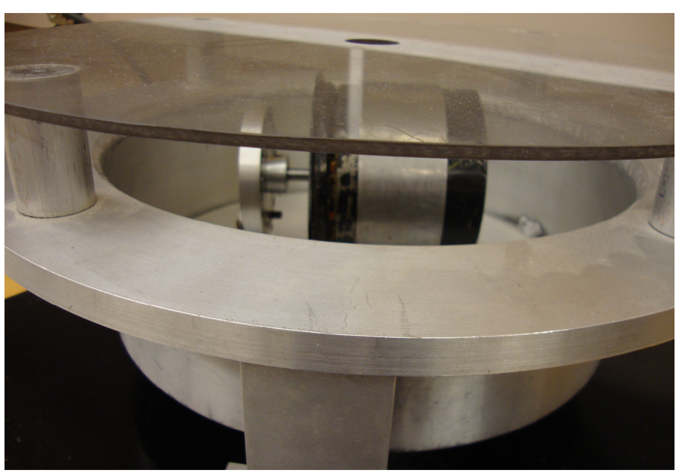

Figure 3. Transmissibility/Isolation test stand

Signals and domains are challenging concepts where mass unbalance can help improve understanding via experimental data. Critical speeds and phase relationships are demonstrated for the unbalanced two-plane test stand. As the stand's unbalanced flexible rotor is operated at increasingly high rotational speed, the vibration vector is tracked, showing the increase in magnitude and corresponding phase shift at each critical speed (and drop in magnitude as the speed moves past the critical speed. The Bode plot in figure 4 shows how amplitude peaks and phase shifts as a rotor transitions through its first critical speed.

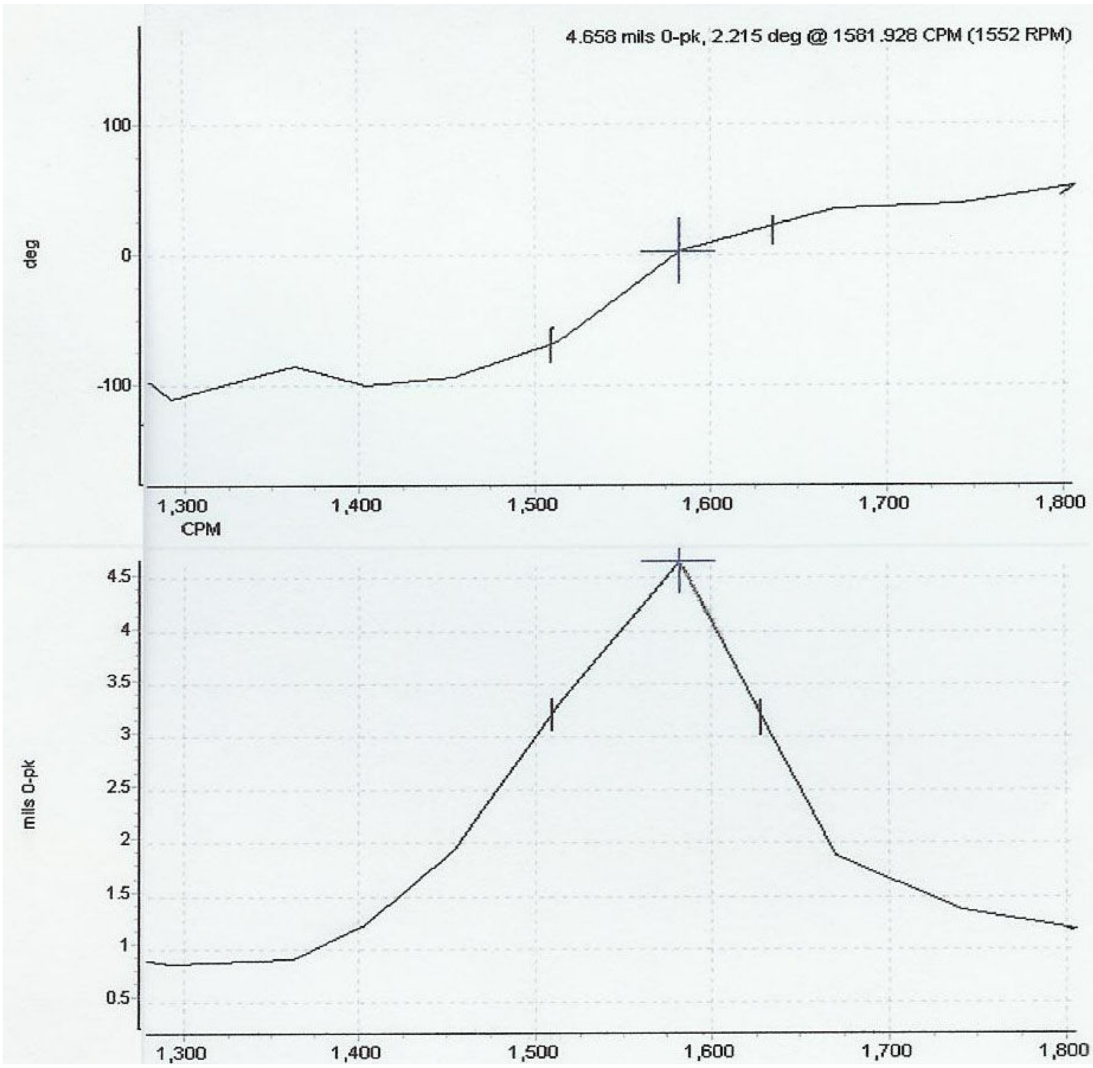

Figure 4. Coast down test data shows a critical speed at approximately 1580 RPM

Mass unbalance is the first machinery fault introduced in the course due to its simple sine wave signal. Mass unbalance occurs in all rotating equipment to some extent, and corrective procedures are well-established. To identify mass unbalance, typically vibration velocity spectra and perhaps time waveforms are measured in at least one radial direction and in the axial direction. For an unbalanced rotor that is centered between bearing supports, the radial vibration amplitude will be much greater than the axial amplitude and the waveforms will be nearly sinusoidal. Static unbalance is the most straightforward type, with all the eccentric mass being concentrated along one side of the length of the rotor, creating a single heavy side. Couple unbalance is the most destructive type of unbalance, when the mass distribution causes equal and opposite forces on the bearing supports. Dynamic unbalance is the common type, combining the effects of both static and couple unbalance and requiring two or more correction planes to reduce the vibration forces[3].

The appropriate balancing procedure is determined by the ratio of rotor length to diameter, the rotational speed at which balancing will be done, and the rotor's first critical speed[7]. While single and dual plane techniques are used with software to balance two rotors, single plane vector calculations and plots are utilized to highlight the basic balancing procedure with an emphasis on development and use of force vectors in the balancing process.

The basic balancing procedure is based on recognition that, while force caused by mass unbalance cannot be measured directly, the resulting vibration vector can be measured and is linked to the force vector by a proportional magnitude and a constant phase lag. The magnitude proportionality ratio and the phase lag can be determined experimentally. A single-plane balance procedure entails measuring the original vibration vector's magnitude and phase; installing a known additional trial mass at a designated location; then measuring the original plus trial vibration vector. The trial mass is then removed. Either graphically or mathematically, the original vector is subtracted from the original plus trial vector to determine the direction and magnitude of the trial vector (vibration caused by the trial mass). The ratio of the original to trial vector magnitudes gives the proportionality constant for determining the correct mass to add (or remove) to cancel out the original mass unbalance. The sweep angle from the trial vector to the original vector denotes the phase shift needed from the trial mass location to the new correction mass location. The corrected vibration vector is then measured to determine if the rotor is adequately balanced, or if the procedure should continue.

Figure 2 shows an example vector plot from a single-plane balance. The original, original plus trial, and correction vectors are plotted from measured vibration magnitude and phase data. The trial vector can be determined by finding the difference between the original and original plus trial vectors either graphically or analytically. The magnitude of the trial vector relates directly to the trial mass size. The magnitude ratio of original to trial vector gives the proportionality constant between mass and vibration, which serves as a multiplier to go from trial mass to required correction mass. The angle from the trial vector to the original vector defines the position shift needed from the trial mass location to the correction mass location. The correction vector indicates the vibration magnitude after one balancing procedure iteration. If the correction vector magnitude is sufficiently low, the procedure is complete. If not, additional iterations are required. Dual-plane and multi-plane balancing procedures are relatively similar, with the added complication of cross effects. A trial mass is still added to each plane where balance masses will be added or removed. When the trial mass is installed, vibration vector components known as cross effects appear in the other plane(s). The students learn to complete both balance procedures using software but only do single-plane vector calculations due to time constraints.

The students get their first exposure to balancing by taking a field trip to the Kirby Risk ServiCenter, a local ISO 9000-certified facility that provides shop balancing of large rotors as one of its many services. Shop balancing requires removal of the rotor from a machine, and field balancing is done with the rotor in its normal operating environment. Starting solely with the shaft, the rotor is balanced on a dedicated test stand. If multiple components are to be mounted on the rotating shaft, they are added one at a time and balanced again as each new component is installed. This trip affords students the opportunity to see dynamic balancing in a carefully controlled environment where the vibration signal goes directly from the rotor to the vibration sensors. When the student teams subsequently complete their own field balancing procedures, the vibration signal travels from the rotor through rolling element bearings before reaching the accelerometer(s) detecting the signal. The vibration may also be affected by the rotor's power supply and other system components. Field balancing is a process that balances the entire rotating element as one unit and as installed in the field.

Mass unbalance is only one of many types of machinery faults with raised vibration amplitude at the machine's operating speed. Determining if mass unbalance is truly the vibration source can be addressed through various other testing techniques such as orbit plots (Lissajous plots) and checking if phase shifts with the position of the phase detector. The four-run, no phase balancing technique offers another practical approach for balancing a rotating element when phase measurements are not possible. In this method, the original vibration displacement is measured, then a known trial mass is positioned and resulting displacement is tested sequentially at three known locations. As figure 5 illustrates, a scaled circle is drawn on polar plot paper to represent the original vibration. Scaled arcs are drawn from each of the trial mass angles on the original vibration circle. The region of intersection defines the magnitude of the "trial" vector needed for the proportionality constant and the angle where the correction mass should be placed.

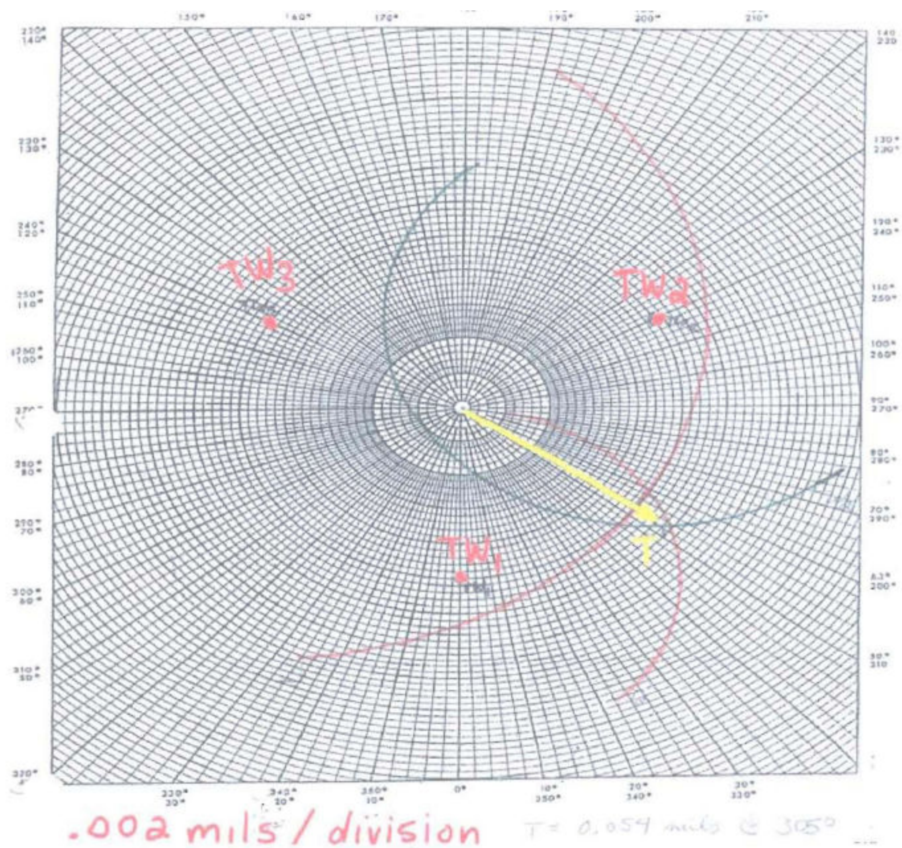

Figure 5. Four-run, no phase balancing plot from a student team's fan project[8]

Use of mass unbalance to address theoretical concepts can be implemented without special equipment, though its effectiveness cannot be attested by the authors. In order to reinforce theory and develop experimental skill, a small test stand that allows for introduction of a known mass unbalance and equipment for measurement of basic vibration is needed. Figures 6 & 7 show the balance test stands and the sensing elements used for balancing in MET 31700. Table 1 lists the course data acquisition and monitoring equipment. Several items provide duplicate functions and serve primarily as backup equipment.

Table 1: MET 31700 Course Data Acquisition Equipment

Equipment	Function
dataPAC 1500 data collectors	Store and process machinery monitoring data; balancing, startup-coastdown testing, etc.
accelerometers	Transducers
Emonitor software	Monitoring route definition and long-term database
Laser tachometers	Rotational speed and phase sensor
ZonicBook data acquisition system	General vibration testing, multi-plane balancing, critical speed testing, et cetera
ez-Balance, ez-Analyst, ez-TOMAS software	Software with Zonicbook for balancing, structural dynamic testing, and monitoring
IRD Model 890 data collectors	Back-up machinery monitoring
photocells	Phase and speed sensor for the Model 890

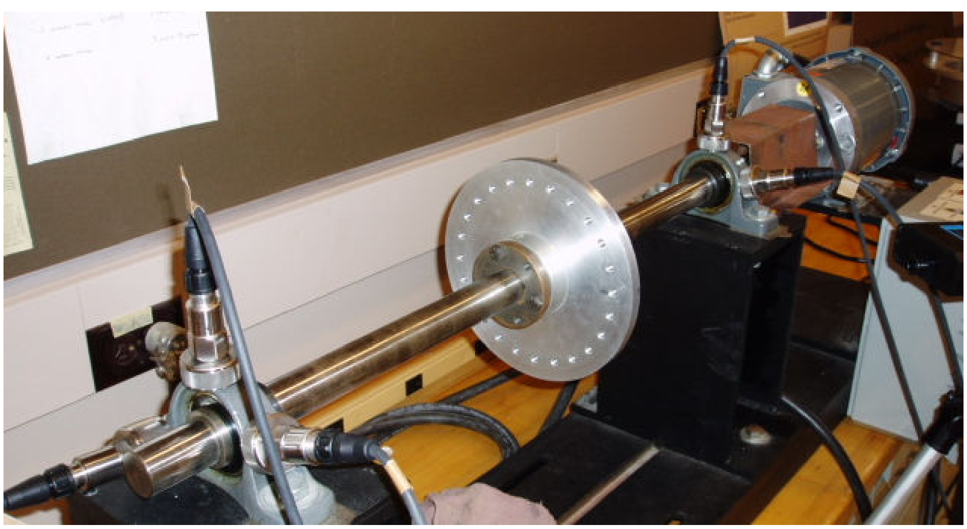

Figure 6. Single Plane Balance Stand

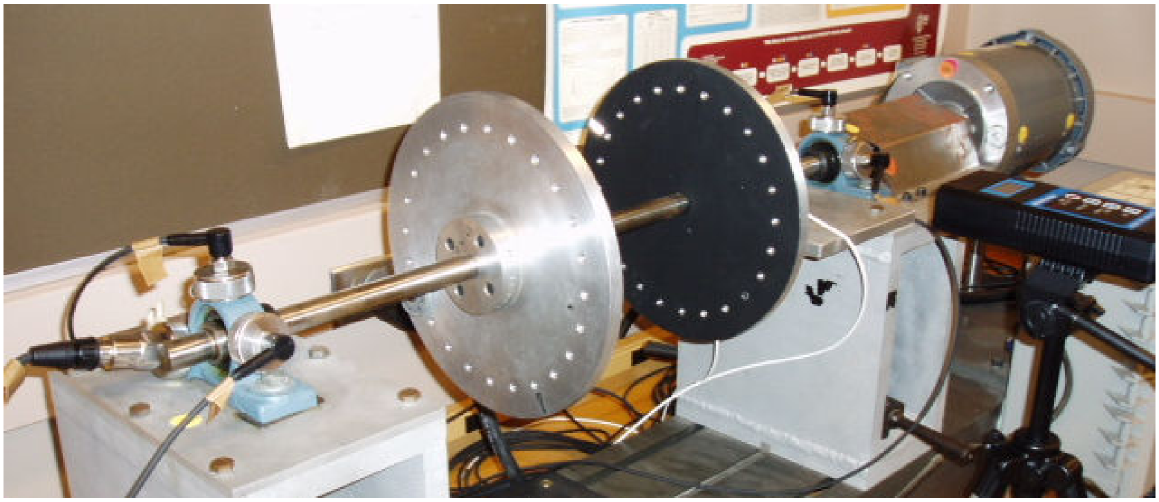

Figure 7. Dual Plane Balance Stand

Table 2 MET 31700 Relevant Course Core Learning Objectives

Core Learning Objective	Mass Unbalance role	Mastery (if mass unbalance role is significant)
Select appropriate vibration isolation for a given machine or other vibrating system.	Provides known source of forced vibration for experimental selection of proper isolation	Students successfully identify proper isolators from experimental data and from catalogs. About half fully master related design concepts while nearly all demonstrate functional understanding.
Experimentally determine the period and first natural frequency (critical speed) of a machine/component.	Dual plane balance stand and software used to demonstrate phase shift and amplitude changes as a rotor is driven through two critical speeds.	Students recognize natural frequencies from an impact or bump test. More than half consistently succeed in finding critical speeds.
Enhance collection of machinery vibration signals through basic signal processing.	Shows real discernible link between time and frequency domains	N/A
Analyze machinery vibration frequency spectra to correctly diagnose machine problems.	First machinery fault; provides fault where students can then correct the problem.	Nearly all students succeed in identifying the most common machinery problems. A majority can diagnose more complex problems.

Mass unbalance factors into instruction for a number of course core learning objectives. Table 2 lists the relevant objectives and the role of mass unbalance in their achievement. Assessment of student learning for the listed objectives is accomplished through tracking of scores on individual examination questions, including evaluation of experimental data. Additional learning assessments involve rubric-based evaluation of semester projects and observation of student performance within the laboratory setting. One of the challenges for any machinery condition determination is to sort through a number of very similar vibration signatures for differing problems. This is particularly important for mass unbalance, because it can only be corrected when phase is stable. This typically occurs when mass unbalance is the only significant problem. Students learn to recognize basic signatures for mass unbalance, misalignment, looseness, and various other root causes of machine vibration. Additional testing techniques such as phase at multiple locations are presented to help distinguish the various problems so others can be corrected before mass unbalance is tackled.

Conclusions

Mass unbalance can serve as an effective vehicle for conveying machinery vibration concepts to MET students. As a pervasive physical source of vibration in rotating equipment, it can help students understand vector relationships, provide experience with a number of experimental structural dynamics techniques, and both visually and audibly show good and bad isolation choices. Full implementation of mass unbalance as an instructional tool requires at least one dedicated piece of rotating machinery and basic dynamic test equipment/software.

Bibliography

1. Thomson, W.T. 1988. Theory of vibration with applications, 3rd edition. Prentice-Hall.
2. Thearle, E.L. 1934. "Dynamic Balancing of Rotating Machinery in the Field", Trans. ASME, 56, 745-753.
3. Eshlemann, R.L. 1999. Basic machinery vibrations: an introduction to machine testing, analysis, and monitoring. VIPress, Incorporated, Clarendon Hills, IL.
4. Eshleman, R.L. 2005. Balancing of rotating machinery. Vibration Institute.
5. MET 317 course web site, www.tech.purdue.edu\met\met317.
6. Wireman, T. 1998. Developing performance indicators for managing maintenance. Industrial Press, New York.
7. ISO 1940-1:2003. Mechanical vibration: Balance quality requirements for rotors in a constant (rigid) state, Part 1: Specification and verification of balance tolerances.
8. Shulkin, I., Ochiai, R., & Leonetti, J. 2009. MET 31700 Single plane balancing versus four run/no phase balancing project (unpublished technical report).