Session 2159

An FFT Spectrum Analysis Laboratory for Undergraduate Vibration or Instrumentation Courses

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Abstract

A complete spectrum analysis laboratory experiment is described. It is intended for mechanically oriented, introductory instrumentation classes, and requires students to diagnose mechanical problems in a machine with rotating components. Equipment requirements are modest. The experiment has been conducted with a sophomore-level class, and practical observations that may increase its educational value are included.

Introduction

Many undergraduate measurements or instrumentation classes include a section on the frequency domain and Fast Fourier Transform (FFT) spectrum analysis. This paper describes a practically oriented FFT laboratory that can be carried out with commonly available equipment and software. Students gather data from a rotating machine such as a lathe in a single laboratory session, generate an amplitude spectrum as 'homework', and then use it to identify problems in the machine. The intent is to instill a practical understanding of the frequency domain, via exposure to spectrum analysis.

The experiment has been carried out twice by the author in the course "AET 210, Measurements and Testing", offered by the Department of Manufacturing and Aeronautical Engineering Technology (MAET) at Arizona State University – East (ASU-East). All students successfully completed it with only occasional 'coaching', and subsequent informal polling showed the majority were enthusiastic about this lab. The written lab procedure is available online[1], and can illuminate the discussion to follow. The 15-page procedure includes detailed instructions for data reduction, sufficient for students with only a basic knowledge of spreadsheet use. It has been revised based on experience with the students, and contains some explanatory material in addition to the necessary procedural steps.

This lab should follow classroom lectures explaining sine waves, Fourier series, the frequency domain, digital data acquisition, and at least a brief introduction to the uses, concepts, and practicalities of spectrum analysis. Many introductory textbooks for measurements or instrumentation courses address these topics.[2,3] A prior laboratory in which students learn to use data acquisition equipment is also useful.

Software and Equipment Requirements

1. A digital data acquisition device, with associated software.
2. A PC, with the "Excel" spreadsheet software package installed.
3. A small, low-voltage DC motor to be used as a tach-generator.
4. A "tach wheel" attached to the motor shaft.
5. A mounting bracket for the motor.
6. A machine with several rotating components, as an object to be tested.
7. A hand-held tachometer.

Only one data acquisition device was needed in the lab, and only one PC, at least for classes of about a dozen students. Inexpensive ADC 'cards' for PC's are available from "radioshack.com", "rainbowkits.com" and other sources for under $100, although the author has no experience with them. The sampling interval (Δt seconds) of the data acquisition equipment determines the maximum observable frequency on the resulting spectrum, as per the Nyquist frequency $f_N = 1/(2\Delta t)$. The highest shaft speed one can successfully observe on the spectrum will be f_N Hz. Engineering schools should generally have adequate digital data acquisition devices on hand; a Hewlett-Packard "Datalogger" with the associated "Benchlink" software is in use at ASU-East.

The sensor for the experiment is a small DC motor used in reverse: when the shaft is held against a moving surface, the motor spins and produces a voltage. Inexpensive DC motors are available for as little as $3 at hobby stores, but the cheaper ones have small shafts and are easily damaged. A better choice is a small, used DC motor obtained from an electrical scrap yard. Simple, well-made motors sell for between $5 and $20. The author suggests low voltage motors (3-12 volts) about 5 - 10 cm long, that turn smoothly and have only two lead wires. Larger shaft sizes are easier to work with, and it's useful to have a 'spare'. The tach wheel to be attached to the motor shaft can be made in a machine shop, with an O-ring stretched around a groove in its periphery; care should be taken to ensure it runs true, and that it is large enough to engage the surface to be measured. There are many commercial sources for tachometers, tach-generators, and accessories, such as McMaster-Carr, Servo-Tek Products Co., Electrocraft and many others, if professional equipment is desired. However, makeshift sensors as described here perform very well.

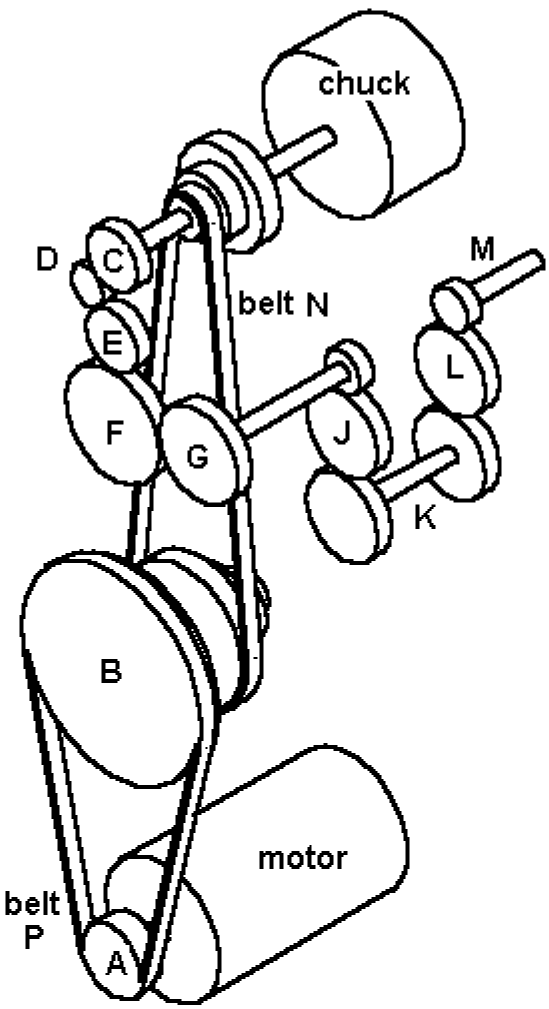
A machine must be selected for the students to test. It can be helpful to show students the moving parts, so a machine that offers easy access to its workings is a good choice. An older machine may have some obvious problems for the students to identify; a well-worn lathe was used for this lab at ASU-East, with good results. Machines that generate periodic shock loads, for example from solenoid actuators, may overcomplicate an introductory experiment. At least one company, SpectraQuest Inc. of Richmond, Va., makes a test bed specifically for teaching spectrum analysis, although such a machine is not necessary for this type of experiment.

Once the machine is chosen, a bracket should be fabricated to hold the tach wheel against a rotating shaft or other moving surface. A hose clamp around the motor body, some cabinet hardware and a C-clamp will often suffice.

Data reduction is accomplished on a PC with a common spreadsheet program. This is quite sufficient for an introductory lab. Dedicated spectrum analyzers with many convenient features are available and could certainly be used. A spectrum analyzer is useful for illustrating the advantages of "averaging" and "windowing", for example. Manual data reduction with a spreadsheet, on the other hand, provides an opportunity to learn more about the specifics of FFT application, and it makes spectrum analysis seem more accessible. It's something students can imagine doing at home, or with a data file they may have on disk.

Preparing for the Lab

It is recommended that the instructor carry out this lab to the point of generating a spectrum before assigning it to the class.



SOUTH BEND LATHE

Item	Speed, RPM
A	1450
B	300
C	640
D	
E	640
F	320
G	455
J	57
K	91
L	57
M	95
N	103
P	235
Tach	______

Elec. Line: 60 Hz

Figure 1: A 'map' of the lathe used for the ASU-East experiment.

Prior to the lab, prepare a drawing showing all the moving parts in the machine. Each part should have a name or a label, and its speed should be noted. Supplying this information to the students will save considerable time in the lab. Include the rotational frequency of any belts, chains, or other moving parts, as well as the speed of the DC tach-generator. Ensure that the machine's speed is reasonably steady when making measurements; the lathe used at ASU-East took 10-15 minutes to stabilize. The laboratory can be completed in about 75 minutes of class time, with a class of about 12 students.

Conducting the Experiment

1. The lab provides a good opportunity to show students by example how to properly deal with a necktie, rings, and loose clothing before working with rotating machinery. Other cautionary measures normally taken with machinery are also appropriate.

2. Students should estimate the output voltage from the tach-generator before using it, and compare that with the limits of the data acquisition hardware, to ensure nothing is damaged.

3. When mounting the tach-generator, students should be cautious about overloading the bearings. Only enough force is needed to ensure that the tach wheel turns the rotor. Route and secure wires to avoid entanglement in the machine.

4. The sensor and instrumentation is only set up once at ASU-East, but each student records a different stream of data for analysis. Before each student gathers data, it may be useful to have them check the speed of the instrumented shaft with a hand-held tachometer for later reference. There should be no sudden change in average shaft speed as data is taken, although a gradual drift of a few percent is tolerable, and sometimes unavoidable.

5. A few minutes of voltage data from the tach-generator should be saved to disk, with a small sampling interval. At ASU-East, the sampling interval was 0.037 seconds, and each student took approximately two minutes of data. Most students had 2048 usable data points, although an introductory lab could be successful with as few as 256 points. (An FFT algorithm is used for data reduction, and that requires exactly 2^n data points, as explained in the lab instructions.) Time permitting, students may want to view or monitor their data in the time domain to ensure it's usable. On occasion, the tach wheel may momentarily break contact or some other 'glitch' may occur. Students should leave the lab with a diskette containing their data file.

6. If the instructor intends to devote considerable class time to analysis, each student could be asked to take data under different conditions. For instance, data could be taken with different parts of the subject machine selectively disconnected, or with other artificially contrived adjustments to the machine. When the different spectra are compared, the effects of various components or changes can readily be seen. This was not done at ASU-East.

Data Reduction

1. After the lab, students reduce the data using a spreadsheet program with the aid of the step-by-step instructions in the lab procedure[1]. Students are advised that some 'software-wrestling' may be necessary, but experience with the lab procedure has been positive. Approximately 75% of the students were able to generate the spectrum using the lab procedure without any coaching.

2. The instructions are written for "Excel 2000" only because it is probably the most widely available spreadsheet package with an FFT function. The FFT algorithm is in the "Analysis ToolPak". "Excel 2000" is a clumsy tool for FFT analysis, because it requires a fair amount of manual data reduction, and because an error in the programming of the FFT algorithm must be corrected by the students. Specifically, spectrum amplitude values must be manually divided by the number of data points analyzed, in order to obtain a correct result. This failing can be turned to educational advantage as an example that blind faith in the output of a computer is unwise.

Students at ASU-East are allowed to use alternative software packages if they wish, without faculty support. At least one introductory instrumentation textbook[3] includes software that will perform an FFT analysis on a data file.

3. The raw data file is assumed to have 3 columns: time of day, elapsed time, and voltage, in comma- or tab-delimited format. Adjust the lab instructions if the data acquisition equipment provides a different file structure.

An Example Student-Generated Amplitude Spectrum

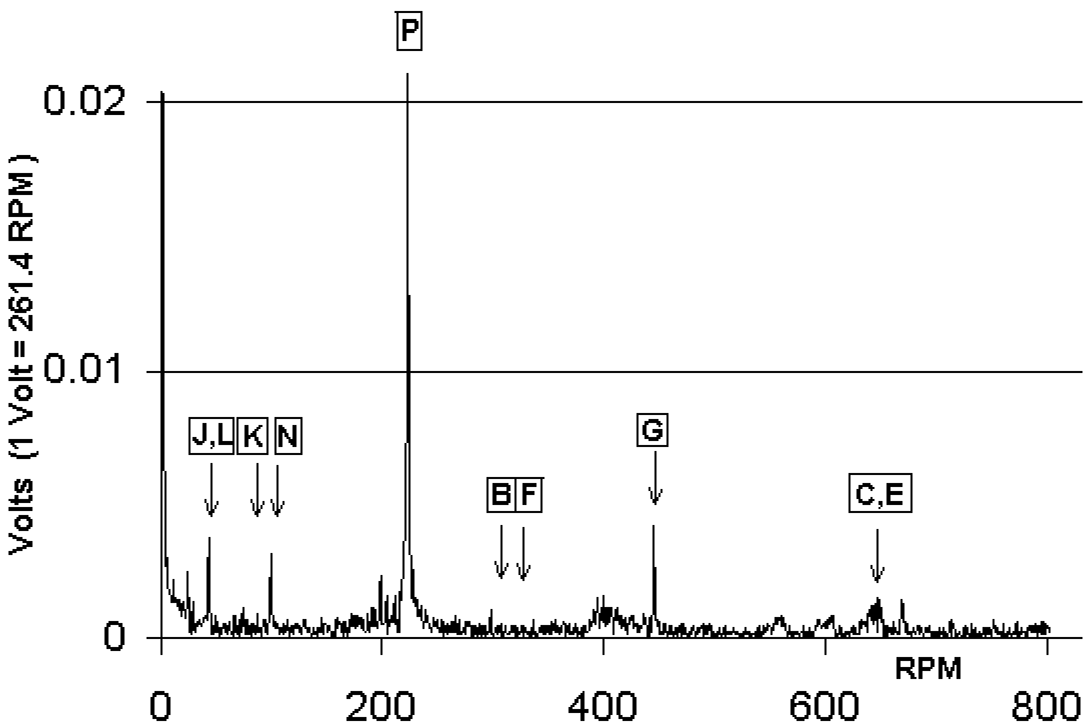


Figure 2: An amplitude spectrum made by a student.

In this introductory experiment at ASU-East, students are only expected to extract some of the more obvious information provided in the spectrum. The student who prepared the spectrum of Figure 2 used it to correctly identify some problems with the lathe, and rule out others. It is accurate, correctly scaled and almost correctly labeled. Letters refer to specific components in the lathe. For reference, peak "P" is associated with a belt that has cracked badly. Peak "G" is the mislabeled second harmonic of "P"; resolution is sufficient to differentiate them. The Nyquist frequency should have been identified. Students should notice that the absence of a peak also conveys information; shaft "F", for instance, is not likely to be in need of attention.

Students often seem to be confused because both the horizontal and vertical axes can be labeled in RPM. Of course, the vertical axis does not really show a speed, but rather a variation or periodic change in speed. It can be useful to review the Fourier series and its relationship to the spectrum as students complete the lab report.

Troubleshooting Notes

1. Failure to apply the FFT to the data: Exactly 2^n data points are needed. Check to see if the column heading cell was inadvertently counted.

2. Generation of a spectrum with excessive noise: Typically, this is caused when a portion of the data file contains some 'zero' data points or a discontinuity. When a spectrum appears suspiciously noisy or 'odd', view the data in the time domain and check for irregularities. The example below shows the same spectrum as above, except that some data has been removed.

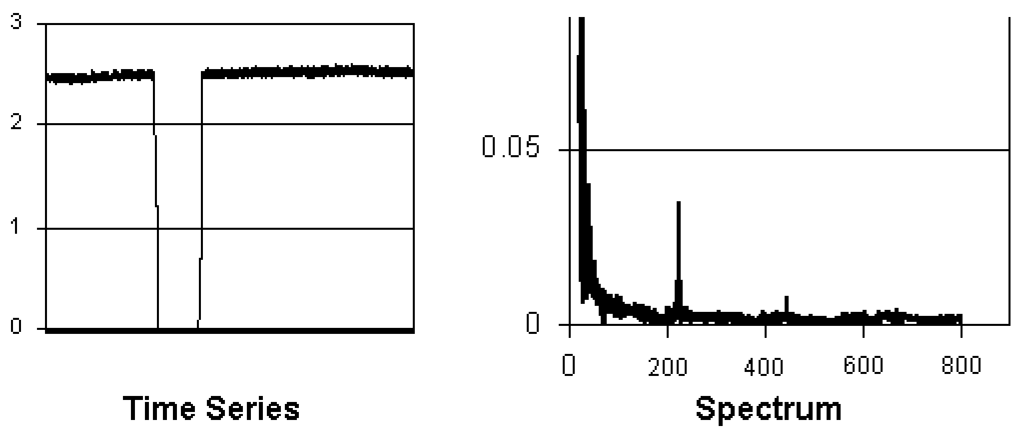


Figure 3: The same spectrum shown in Fig. 2, but with some data removed. Note the low-frequency 'noise'.

3. Generation of a spectrum with no visible peaks: This may be caused by failure to remove the large zero-frequency component from the plotted data.

Conclusion

The spectrum analysis laboratory described here can be carried out with minimal laboratory equipment and software. It is hoped that the lab procedure[1] and this document together will provide sufficient information to easily set up and conduct an introductory lab experiment using the FFT.

References

1. Post, A. M.:"Frequency Analysis Laboratory and Introductory Pages," web site, 2002. **http://ctas.east.asu.edu/post/fftweb/fftlab.htm**

2. Beckwith, T. G., Marangoni, R., and Lienhard, J.: "Mechanical Measurements," 5th ed., pp.130-156, Addison-Wesley Publishing Co., 1995.

3. Figliola, R. S., and Beasley, D. E.: "Theory and Design for Mechanical Measurements," 3d ed., pp. 35-69 and 239-244, John Wiley & Sons, Inc., 2000.

Biographical Information

ALVIN POST has 20 years of industrial experience as a mechanical engineer. He formerly taught at McGill University, and now teaches at Arizona State University East. He received a doctorate in mechanical engineering at the University of Hawaii in 1996, and has interests in machine design and nonlinear dynamics.