

CHAPTER 3

IMPULSE RESPONSE TESTING EQUIPMENT

3.1 INTRODUCTION

The testing equipment and its functions for impulse response testing are described in this chapter. Descriptions of both the hardware and software used for this testing program are provided. The equipment and software was provided by STS Consultants, Ltd. Much of the information in this chapter was provided through either the equipment supplier's product literature or through personal contact with STS Consultants.

3.2 DATA ACQUISITION TOOLS

3.2.1 Hardware

Several pieces of hardware are necessary for the completion of impulse response testing. The major items include an impulse hammer, a digital grade geophone, an amplifier/signal conditioning card, a data acquisition card, and a portable computer. Other necessary equipment includes the connections required to link all these items and a portable power supply.

Impulse Hammer

The impulse hammer is required to apply the impact to the shaft head and to make the force measurement. The hammer used for the testing was the PCB Piezotronics Model No. 086M54. The hammer impulse consists of a nearly constant force applied

over a broad frequency range. The frequency range is determined by the hammer cap which consisted of a hard rubber tip that was capable of generating frequencies up to 2,000 Hz; varying the tip stiffness will lead to a different range of frequencies generated by a hammer blow. Under most temperature conditions, the hard rubber tip consistently provided frequencies from 0 to 1000 Hz.

To complete the force measurement, an integral quartz force transducer is mounted on the striking end of the hammer head. This transducer converts the impact force into an electrical signal that can be digitally analyzed. Quartz is a piezoelectric material that develops an electrical charge proportional to applied pressure or deformation. A micro-electronic amplifier circuit is incorporated into the transducer housing to improve the output signal/noise ratio. The sensitivities for the hammers vary slightly and are determined by the manufacturer before they are shipped. The hammer used for this test had a sensitivity of 0.77 mV/lb (0.17 mV/N). To convert this to a usable force value, the measured voltage is divided by the sensitivity, yielding the force.

Another feature of the hammer is that it is modally tuned to eliminate bouncing (multiple impacts). This means that the hammer head experiences little motion due to the lower natural resonant frequency of the total hammer structure.

Other features of the hammer include the ability to change to softer or stiffer hammer tips to get a better low frequency or high frequency response, respectively. Extenders can also be attached to the non-impact end to increase hammer mass which increases the duration of impact, thus improving the low frequency energy content of the signal.

Digital Grade Geophone

A geophone is required to measure the shaft head velocity. For this study, a SM-6 Geophone Model B by Sensor Nederland b.v. was used. This geophone has a natural frequency rated at 4.5 ± 0.5 Hz. Its sensitivity is rated at $28.8 \pm 5\%$ V/m/s (0.73 V/in/s). The frequency response curve for this geophone is shown in Figure 3-1.

Figure 3-1. Response curve for SM-6 digital grade geophone (adapted from Sensor Nederland b.v. literature)

With the geophone undamped, the curve response does not begin to flatten out until approximately 30 Hz. For this reason, the geophone is modified by a calibrated damping series-parallel resistor network. The effect of this damping resistor network is to extend the low frequency response down to about 8 Hz, and reduce the sensitivity to a calibrated value of 20 V/m/s (0.51 V/in/s). Conversion to velocity is completed by dividing the recorded voltages by the geophone sensitivity.

The geophone is a single-degree-of-freedom type where output is generated by a coil moving through a magnetic field. The voltage in the coil is directly proportional to the relative velocity between the coil and the magnetic field. Either the coil or the magnet is made part of the mass and the other component is attached to the frame (Richart et al., 1970).

Amplifier/Signal Conditioning Card

The amplifier/signal conditioning card is custom built and is housed in one of the expansion slots of a portable computer. This card uses the +12 V power supply of the computer and doubles it to 24 V to power the hammer load cell micro-electronics at a constant current of 4 mA. The hammer specifications states that the voltage supply should not exceed 30 V and the current is not to exceed 20 mA. This card ensures proper voltage and current regulations for the hammer.

The card also contains an amplifier filter for the geophone with switch selected

gain ranges of x1, x2, x5, x10 and x20. By having the choice of different gain settings, the signal to noise ratio (S/N) can be optimized and low voltage signal resolution can be improved. With the 12 bit analog-to-digital (A/D) converter found on the Bakker data acquisition card used for this study, the maximum input range is set at ± 5 V. This range is spanned by 4096 (2^{12}) possible voltage levels that the A/D converter can discriminate (a 2.4 mV resolution). If the input signal only spans ± 2.5 V then only 2048 possible voltage levels can be detected without a change in the gain setting. By changing the input voltage range (gain) to x2, the ± 2.5 V signal is boosted to 5 V and all 4096 voltage levels can be utilized over the new range thus improving the resolution to 1.2 mV.

Data Acquisition Card

A data acquisition card is required to monitor the force and velocity responses. This card is housed on one of the expansion slots of the portable computer and is directly accessible by the data acquisition software by means of an assembly language routine. The card for this testing program is the BE485 data acquisition card by Bakker Electronics of Holland.

The card has on-board memory allowing the data acquisition to occur at full speed before being transferred to the computer's memory. The card has 4 input channels, two of which are used for connection of the geophone and the hammer. Another useful feature of the card is the pre-trigger function. Sampling is taking place at 10,000 Hz with a total of 1024 points being recorded. The pre-trigger allows the card to continuously take data until a trigger is received. At that point, 824 additional points beyond the trigger and 200 points before the trigger are recorded. This allows for accurate identification of the

time of impact and the geophone response.

The BE485 also has a feature called simultaneous sample and hold, meaning that each channel has a sample/hold amplifier. This allows simultaneous sampling and A/D conversion of the hammer and geophone channels. A sample/hold amplifier continuously "samples" the input analog signal until a digital signal switches it into a "hold" mode. At that point, the current analog voltage is kept constant long enough for the analog/digital converter on the card to digitize the signal. Once the signal is digitized, the amplifier is returned to the "sample" mode.

Portable Computer

A portable computer is required for running data acquisition and analysis software, viewing data, and storing data. An IBM-compatible, Intel chip based 486 computer running at a clock speed of 33 MHz with a math coprocessor was used for this study. It had 4 MB random access memory (RAM) which allowed sufficient space for running the necessary software applications. To facilitate proper program execution, the computer needs to have some of the RAM available as expanded memory.

Two full-sized expansion slots are required for the installation of a data acquisition card and an amplifier/signal conditioning card. An LCD screen with VGA display was used to allow the operator to easily view the data in an outdoor environment. With an LCD screen as the outdoor light intensity increases, the ability to view the screen is not diminished as with a normal monitor.

The computer was also equipped with a 3½" floppy drive and a 170 MB hard drive to easily facilitate data storage and data transfer to other computers. The computer is

powered by means of a 110 V AC power supply. In the field, this was achieved by means of a Honda EM650 portable generator. It is necessary for the generator to be properly grounded, otherwise sinusoidal background noise such as the 495 Hz cycle shown in Figure 3-2 or a 60 Hz alternating current noise is likely to appear on the geophone response, masking the desired data.

Figure 3-2. Example of electrical interference caused by improper grounding

3.2.2 Software

All the software for the data acquisition and analysis was completed using the

ASYST programming language developed by Keithley Metrabyte except for the assembly routine written to access the BE485 acquisition card. The ASYST programs were written by Dr. Allen Davis and Bernie Hertlein of STS Consultants, Ltd and the assembly routine was developed by the CEBTP in France.

The software is prompt oriented making extensive use of function keys. To take new data, the operator is asked for logistical information about the site and shaft to be tested. After all the information is provided, the software pre-triggers the impulse hammer and tells the operator to proceed with testing. Upon hammer impact (triggering), the force and velocity data are recorded. The data is then presented on the computer screen and the operator is asked to either accept or reject the data. If the user rejects the data, the test is repeated until a satisfactory result is obtained. If the user accepts the data, it is stored in an array and the test is repeated for as many times as required by the operator for averaging. Usually three or four tests are performed to check repeatability. The coherence between the previous and the newly acquired data array is calculated by the program to aid the operator in determining the repeatability of each test. After all the data has been acquired, the averaged data is saved to the hard disk where it can be viewed at a later date.

3.3 DATA PROCESSING

3.3.1 Data Analysis

All the force and velocity data are sequentially acquired with time, but the impulse response method analyzes the results in the frequency domain. To move from the time

to the frequency domain, it is necessary to perform a Fourier transform on the force and velocity data.

To complete the time to frequency transition with the ASYST language, the data array is subject to ASYST's *FFT* command. This command invokes the Fast Fourier Transform (FFT) algorithm. The magnitude of the imaginary and real components of the complex array returned by the *FFT* command is then computed. A typical result of this function on force versus time and velocity versus time traces is shown in Figure 3-3.

Figure 3-3a. Fourier transform of force signal

Figure 3-3b. Fourier transform of velocity signal

Note that the force and velocity plots mirror themselves as a result of the periodic nature of the FFT. The data is plotted over the 10,000 Hz sampling rate. Due to the mirroring, only the first 5,000 Hz is available for analysis purposes. Recall, that the impulse hammer only inputs frequencies up to a maximum of 2,000 Hz with the hard rubber tip. This limits the useable frequency from 0 to 2,000 Hz. Because the geophone

response curve is flat only above 8 Hz and its natural frequency is about 4.5 Hz, inaccurate data are recorded in this range. To account for this, the first index of the Velocity/Force function array (all Velocity/Force data is stored by ASYST in a 1024 index array) is set to zero and the second array index is set to half of the third array index. These manipulations have some effect on the stiffness calculation, but the stiffness values are primarily used for comparison purposes between similar sized shafts.

After the data are transformed to the frequency domain, the velocity is divided by the force. At this point, all the data has been recorded as voltages. To convert to engineering units, V/F is multiplied by a scaling factor determined by the sensitivities of the geophone and impulse hammer. For the data recorded as part of this testing program, the scaling factor was 8.5×10^{-6} (m/s)/N.

3.3.2 Digital Filtering

To remove some of the "noise" often encountered under field conditions with non-destructive testing, digital filtering is necessary. Two ASYST commands called *FILTER* and *SMOOTH* were used for this purpose. By filtering the data resonant peaks became more obvious, thus reducing subjectivity in the length measurements.

The *FILTER* command was used in the time domain to "clean" the velocity trace. This command computes a finite impulse response filter using a windowing technique that takes an infinite duration filter time response and applies a window to it. It forms a finite duration impulse response that approximates the desired time response (ASYST 4.0, 1992). A Blackman window filter was used for this case because it is best known for minimizing "ripple" effects at the edges of the data. The *FILTER* command is defined as

a lowpass filter, which means that it does not alter the low frequency content of the signal. Figure 3-4 shows an example of the multiplying factors used for a lowpass filter. A passband end of 800 Hz was used with a transition width of 500 Hz. This command practically reduced the signal to zero above 1,300 Hz. This frequency was chosen as the cutoff value because above 1,300 Hz, the coherence of the signals varied substantially.

Figure 3-4. Example of a lowpass filter response (adapted from ASYST 4.0, 1992)

After the velocity trace was filtered, it was subject to the *FFT* command as described previously. The force trace was unaltered because the impulse hammer input gives a good "clean" signal. After the velocity and the force are transferred to the

frequency domain and the velocity is divided by the force, the *SMOOTH* command is applied to the resulting quantities before they are finally presented as the impulse response result.

The *SMOOTH* command is used to filter data that is in the frequency domain. It is based on the assumption that the signal spectrum (desirable data) dominates lower frequencies and the noise spectrum (undesirable data) dominates higher frequencies (Astheimer, 1992). Thus it is a lowpass filter that for this case was set to eliminate all frequencies with periods shorter than 2 data points (less than every 19.5 Hz based on the acquisition rates used for this study). This command is also based on the Blackman window method.

3.3.3 Data Presentation

To illustrate what the current impulse response testing software allows the operator to view for data analysis, the following figures are presented. After a data file is loaded into memory or after the hammer triggers the data acquisition cycle, Figure 3-5 appears on the computer display.

Figure 3-5. Common ASYST screen showing acquired data (a) Force vs. time
(b) Velocity vs. time (c) Signal coherence (d) Impulse response

To better illustrate the force trace, Figure 3-6a show the force versus time and Figure 3-6b shows the force versus frequency trace. Note the symmetry in the force impulse and the decrease in energy with increasing frequency.

Figure 3-6a. Typical force vs. time trace

Figure 3-6b. Typical force vs. frequency trace

A typical velocity trace was presented in chapter 2 for the seismic echo test. Figure 3-7 shows the velocity response after it has been subjected to a Fast Fourier Transform.

Figure 3-7. Typical velocity vs. frequency response

The usefulness of the coherence function in determining the repeatability of results is shown in Figure 3-8. Figure 3-8a shows good coherence (approximately 1:1 correlation) to 1,000 Hz indicating good repeatable data. Figure 3-8b shows poor coherence and indicates the test should be repeated. Before repeating, the geophone and impact contact surfaces should be checked along with the geophone coupling.

Figure 3-8a. Example of good data coherence

Figure 3-8b. Example of bad data coherence

For examples of final impulse response results, see some of the case histories presented in chapter 2 or look at Figure 3-5d. These illustrations are meant to show some of the functions of the software in its current form and to show what the general shapes and magnitudes of the various signals are for "good" data.