INSTRUMENTATION FOR

RELATIVE CYLINDER POWER MEASUREMENT ON

INTERNAL COMBUSTION ENGINES

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ABSTRACT

The goal of design projects is to introduce students to designing mechanical systems in the ETME475-Mechanical Systems Design course. Purpose of this project was to design a sensor assembly to measure relative power of individual cylinders on an internal combustion engine. Basic sensor assembly was completed as a laboratory requirement for the course. The sensor assembly consists of an optical encoder, a sensor holder frame and a handle. A pulley is attached to the shaft of the encoder. An O-ring is fitted over the groove of the pulley. When pressed against it, the pulley can ride on crankshaft belt of an idling internal combustion engine. Pulses generated by the encoder are acquired and stored in a file using National Instruments[1] PCI 6023E data acquision board and National Instruments LabVIEW data acquisition software. Stored data is processed using LabVIEW software and results are displayed. Variation of frequency of the signal is proportional to the belt speed. Belt speed is related to the power generated by individual cylinders on the engine. During power stroke belt speed increases, whereas during compression stroke belt speed decreases. Therefore magnitude of peaks on a plot of frequency as a function of time (or, in this case, sample number) gives an indication of relative power generated by each cylinder. Plot is generated for two revolutions of the crankshaft.

NOMENCLATURE

D = Engine crankshaft pulley diameter
I = Moment of inertia of the moving engine parts
N = Engine idling speed, rpm
ΔN = Change in engine speed, rpm
ΔP = Change in engine power
SR = Acquisition sampling rate, samples/s
T = Torque generated by a cylinder during power stroke
d = Encoder pulley diameter
f = Frequency of encoder pulses, Hz
n = Encoder angular velocity, rpm
ppr = Pulses generated per revolution of encoder

α	= Engine angular acceleration	
$\propto$	= Proportional to	
θ	= Angular position at the end of power cycle	
θ_0	= Initial angular position	
ω	= Engine angular velocity	
ω_o	= Initial engine angular velocity	
$\Delta\omega$	= Change in angular velocity	

INTRODUCTION

Students in the Mechanical Engineering Technology program are required to take at least one Systems Design course during the last year of their program. As part of the requirement for this course, students are assigned to design a system or systems that require use of the knowledge they have acquired in lower level courses. Sometimes they are assigned a group project if the project is large enough.

The Sensor Assembly design project was assigned to one student during spring semester of 2000. Student has finished the mechanical design and construction of the sensor assembly. Initially a DC generator was used as a sensor. Very limited testing was done on bench. Rest of the work was done by the first author during fall semester of 2001.

The purpose of this paper is to describe the sensor and instrumentation used for relative cylinder power measurements on an internal combustion engine and convey experiences we had during the design, construction and operation of the system.

RELATIVE CYLINDER POWER MEASUREMENT

I am not sure how new engine diagnostic machines measure relative cylinder power on internal combustion engines. To my understanding, our old (1984) SUN Interrogator Engine Diagnostic unit kills the ignition of cylinders, one at a time, and measures drop in average engine speed. Drop in engine speed can be related to relative power of a cylinder. Author could not find a way of using SUN diagnostic machine on new car engines. Most engines do not have open ignition coils or distributors where one can connect grounding lead of the diagnostic unit. In addition, most car computers try to maintain an average engine idle speed at a fixed value even if one cylinder losses its power.

With the sensor assembly, the goal is to measure change in instantaneous speed of an engine during one power stroke for each cylinder. Variations in instantaneous engine speed during one cycle (two revolution of the crank shaft) are reduced by the engine flywheel and moment of inertia of the running engine. Therefore actual variations in speed will depend on engine size and design. One can only estimate cylinder's relative power using change in engine speed during power stroke. For a simple case of constant angular acceleration, and assuming that acceleration starts from the same initial speed for each cylinder, as shown below, power generated by a cylinder is

proportional to square of increase in engine speed. In real life, angular acceleration is not constant since torque is not constant. Nevertheless change in engine speed is an indication of relative cylinder power. For constant angular acceleration, governing equations are:

$$\omega^2 = \omega_0{}^2 + 2*\omega*(\theta-\theta_0) \qquad\qquad (1)$$

$$T = I*\alpha \qquad\qquad (2)$$

$$\Delta P = T*(\Delta\omega) \qquad\qquad (3)$$

Substituting equation (1) into equation (2) and using

$$\omega^2 = (\omega_0 + \Delta\omega)^2 \approx \omega_0{}^2 + 2*\omega_0*\Delta\omega \qquad\qquad (4)$$

Equation (3) becomes:

$$\Delta P = \frac{I*\omega_0(\Delta\omega)^2}{(\theta-\theta_0)} \qquad\qquad (5)$$

Since I, ω_0 and $(\theta-\theta_0)$ are either same or approximately same for each cylinder,

$$\Delta P \propto (\Delta\omega)^2 \propto (\Delta N)^2 \qquad\qquad (6)$$

CALCULATION OF INSTANTANEOUS BELT VELOCITY

As mentioned above as each cylinder produces power, engine speed will increase. A plot of engine speed versus time will have peaks starting at the firing time of each cylinder. Optical encoder generates pulses as it rotates. One can use period of pulses (time between two pulses) to calculate instantaneous velocity of engine belt. Real time acquisition and processing of such signals requires capabilities that are only available with expensive or specially designed data acquisition boards. One might acquire the signal using Analog to Digital Converter (ADC) channel of a data acquisition board, store the data in a file and process it later. For our optical encoder, such a system will require acquisition rates in excess of 5 mega samples per second for one percent accuracy in the measured period or engine speed.

Five to ten data points are needed to identify a power peak on a graph. Since engine speed and frequency of pulses generated by the optical encoder are proportional, one can plot frequency of pulses instead of engine speed. For one percent accuracy in calculation of frequency one has to capture 100 pulses for each data point on the graph. This amounts to 500 to 1000 pulses per power peak. Therefore, for a six-cylinder engine, one has to capture 3000 to 6000 pulses. To catch each peak and valley of a square pulse train from the encoder one has to sample it at least at a rate of twice the pulse frequency. This means acquiring at least 6000 to 12000 data points per two revolutions of the engine crankshaft. For a six-cylinder engine and for a minimum of five data

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points per power peak one needs at least 30 data points. Thus acquired data may be split into 30 sub-groups and average frequency of each group can be evaluated by dividing the number of pulses captured in each group by the time it took to capture them. The time that it takes to acquire needed number of points (6000 minimum in this case) depends on the acquisition rate and the time it takes for the crankshaft to finish two revolutions. If one selects a right size encoder pulley one can calculate number of samples to be acquired using:

# of samples = 120*(SR)/N

Where acquisition sampling rate, SR, should be at least twice of the encoder pulse frequency, f. After selecting a right size pulley diameter, exact encoder frequency may be calculated using equation (9) given below. Thus

# of samples $\geq$ 240*f/N

The calculated "# of samples" may be rounded to a multiple of number of sub-groups to be used (30 sub-groups in this case).

INSTRUMENTATION

(a). Sensor Assembly

A Globe Industries, Inc.[2] DC generator and an Opto Generic Devices[3] optical encoder were purchased from C&H[4] to be used as sensors. DC generator generates 0.5 V per 1000 rpm. During testing it was found that there was an AC voltage (10 cycles per revolution) on top of the DC voltage generated by the encoder. This AC voltage amplitude was high enough to interfere with the DC voltage generated due to increase in engine speed. Filtering the AC voltage did not improve the situation. Therefore, use of DC generator, as a sensor, was abandoned and optical encoder was used for the design of sensor assembly.

Optical encoder has two channels. Channels #1 and #2 generate about 990 and 1350 pulses per revolution respectively. Channel #1 was used for data acquisition. Although frequency response of the optical encoder, as shown in Table 1, is higher, since it starts loosing some pulses at about 75 kHz, the encoder pulley was sized to operate the encoder at about 50 kHz. Most engines have 600-1000 rpm idling speeds and crankshaft pulley sizes are not same. Therefore, different encoder pulley sizes may be needed for different engines to make it sure that the encoder operates below 75 kHz pulse rate. Since

f = (ppr) x n /60, and   (7)

d x n = D x N   (8)

One can show that the required minimum encoder pulley diameter may be calculated using:

$$d \geq \frac{D \times N \times (ppr)}{60 \times f} \qquad (9)$$

Where $f \leq 75{,}000$ Hz.

Table 1. Technical Specifications for Optical Encoder
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Model No	: H003, 84619
Channel #1	: ~990 ppr
Channel #2	: ~1350 ppr
Max rotational speed	: 3,000 rpm
Supply Voltage	: 3-12 VDC
Frequency Response	: >150 kHz
DPI	: 300/406

Encoder is clamped in a cylindrical housing using a setscrew. Cylindrical housing is welded to one-foot long handle. As shown in Fig.1, with the help of the handle, encoder pulley may be pressed against the crankshaft belt for cylinder power measurements.

(**b). Data Acquisition System**

Our old data acquisition system consists of a TDK 486-66 microcomputer, a Data Translation[5] DT2805, low level, 12-bit data acquisition board and ASYST (version 2.1) software. DT2805 board has a DT707 screw terminal box which can support thermocouple inputs with a reference junction occupying analog input channel "0". Throughput speed with single channel analog input is up to 13.7 kHz at 1X and 10X amplifications. Although writing programs with ASYST is simpler, since acquisition speed of DT2805 board was low for this application, it was not used. Support of ASYST software was discontinued by Keithley[6] in 1993 with version 4.01. No drivers are available for new data acquisition boards.

A new microcomputer based data acquisition system was assembled and used to read the voltages from the sensor. System consists of an AST Pentium-133 microcomputer, National Instruments[1] PCI-6023E data acquisition board, BNC2090 Shielded BNC Adapter Chassis and LabVIEW 5.1.1 software. BNC2090 supports all the inputs that data acquisition board has. Adapter chassis is connected to the board with a flat cable. All ADC, DAC and triggering inputs use BNC connectors. Digital inputs and counters use spring-loaded terminals. Throughput speeds of 200 kS/s may be obtained. The gains on the board can be set by software for each channel. Major specifications for the board are given in Table 2.

LabVIEW software was used to acquire and process the acquired signal. ADC channel 0 was used for the optical encoder. Acquisition start time was triggered by an inductive probe attached to cylinder #1 ignition cable through digital trigger input of the data acquisition board. Encoder

generates 0-5 volt square wave signal. Data is stored into a spreadsheet file.

After acquiring the data, the computer retrieves the stored data, splits it into 30 groups, counts the number of pulses in each group, calculates frequency of each group and plots the calculated sub-frequencies. Some other parameters related with the data are also displayed.

Table 2. Major Technical Specifications for PCI-6023E Data Acquisition Board

Resolution ADC/DAC	ADC Channels (Single ended)	DAC Channels	Programmable Gains	I/O Bits Port0	Counters
12/12	16	2	1, 10, 100	8	2

(c). Programming of Data Acquisition and Signal Processing

LabVIEW[1] software was used to program the data acquisition and processing of the acquired signal. LabVIEW (laboratory Virtual Instrument Engineering Workbench) is a development environment based on the graphical programming language G[7]. All LabVIEW programs have a "Front Panel" which uses "Controls Palette" and a "Block Diagram" which uses "Functions Palette" in their construction. Front Panel is used to control acquisition and/or processing functions of the LabVIEW software. Block Diagram is used to construct the sequence of operations. One uses a wiring tool from "Tools Pallet" to connect inputs and outputs of different blocks (functions) to accomplish a combined task. For example one can use an "ADC" block to acquire an analog data at a specified speed, using a specified channel number, and use "Write to File" block to pick the acquired data and write it into a specified file.

LabVIEW computer program for this project consist of two tasks. First task is to acquire the data and store it into a spreadsheet file. Second task is to retrieve the stored data and process it. For the first task, "AI Acquire Waveform.vi", "Write to Spreadsheet file.vi", "Threshold Peak Detector.vi" and "Waveform Graph.vi" programs are used. "Threshold Peak Detector.vi" counts the number of peaks and displays it. A "calculation block" calculates the frequency of the signal and displays the value. Major input parameters are: Analog channel number to be used, scan (acquisition) rate, number of samples (data points) to be acquired, file name to store the data, and "peak detection threshold". This task transfers the "scan rate", "file name" and "peak detection threshold" to the second task.

The second task consists of a "30sub2.vi" program. In turn "30sub2.vi" program consist of "Read From Spreadsheet File.vi", "Waveform Graph.vi", "Threshold Peak Detector.vi" programs, and "Array Subset", "Array Size" and "Build Array" function blocks. There are no user input parameters for this task. As mentioned above, three parameters are passed to it from first task. "Array Subset" block and "Threshold Peak Detector.vi" program are used 30 times to extract 1/30th of the stored data points and find number of peaks in each group, respectively. Number of peaks is used to find the frequencies of the signals in each group using "Calculation" blocks.

Finally, calculated sub-frequencies are combined into an array using "Build Array" function block and plotted. Error in sub-frequency, scan rate, number of peaks and average frequency of the original signal are calculated and displayed along with some other useful data. Front Panel and Block Diagrams of each task are given in Fig. 2, 3, 4 and 5.

RESULTS

The designed system was tested on electric drive system of our previously designed Wheel Balancing Machine[8,9]. Deceleration and acceleration of a two-pole electric motor was clearly observed. For further testing, the sensor assembly was pressed against crankshaft belt of our 4-cylinder, gasoline internal combustion engine using a fixture. Typical results are given in Fig.2 and Fig.3. As seen in Fig.2, all four cylinders are generating about the same power since all four frequency peaks are about the same. In Fig.3 no peak, on the first cylinder, is seen since ignition cable was removed. A gradual increase in the average speed of the engine is clearly seen as other three cylinders add power.

CONCLUSIONS

A sensor assembly for a relative cylinder power measurement system was designed and constructed by second author to satisfy laboratory requirement of ETME 475-Mechanical Systems Design course. Installing the new data acquisition system, writing the LabVIEW computer program and testing was completed by the first author. Project involved mechanical design for the sensor frame as well as electronics design for instrumentation. This was a successful and a useful project.

Planned extensions for this projects are: (a) incorporate digital triggering using an inductive probe attached to any cylinder ignition wire, (b) find a way to numerically integrate the frequency peaks so that relative power of each cylinder may be displayed numerically, (c) modify the computer program to acquire and display average frequency graph and relative power of each cylinder for a given number of power cycles.

ACKNOWLEDGMENTS

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5. Data Translation, 100 Locke Drive, Marlboro, MA 01752-8528, http://www.datatranslation.com/.
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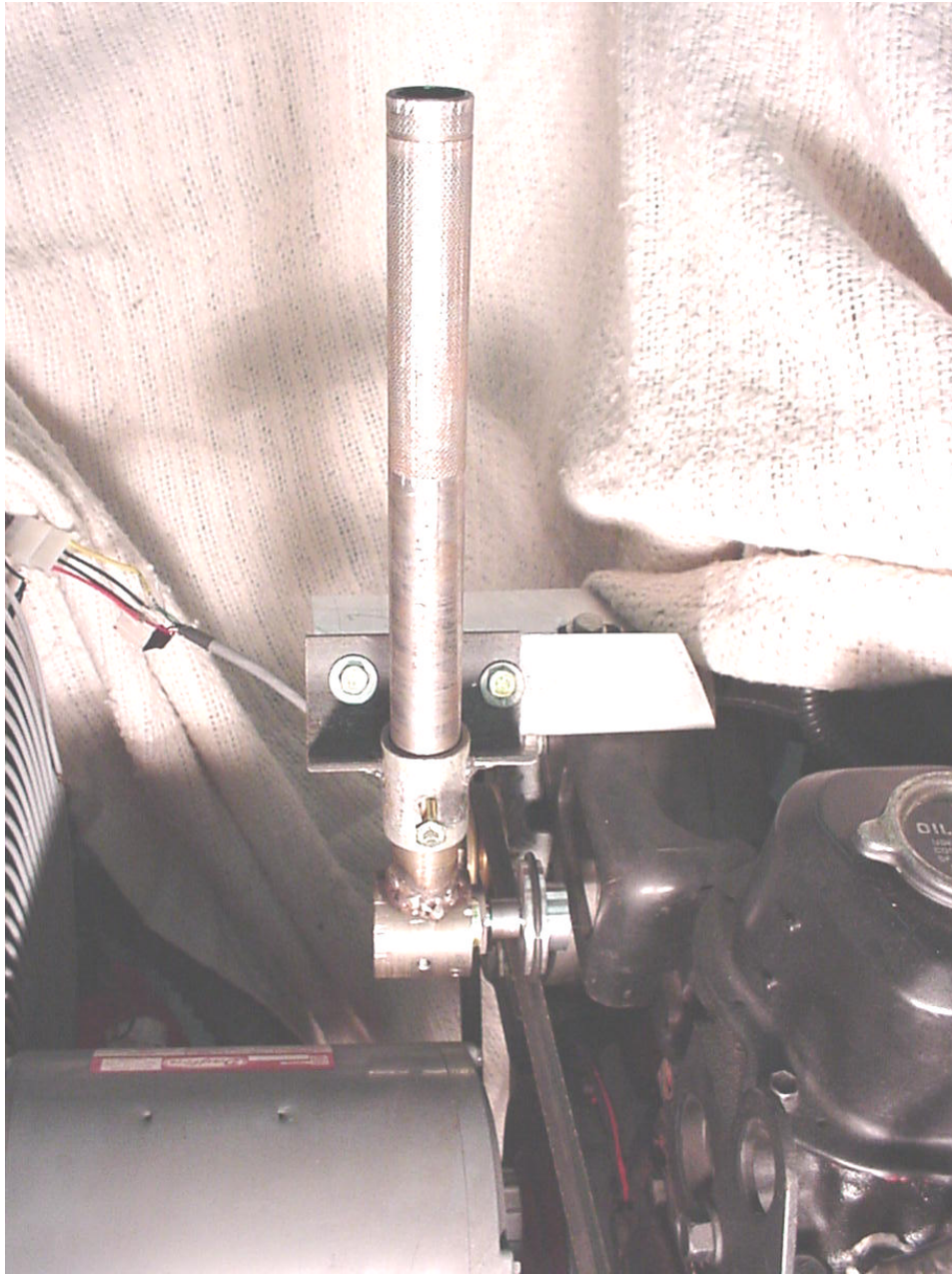
Figure 1. Sensor Assembly as Being Held by a Fixture Against Engine Belt.
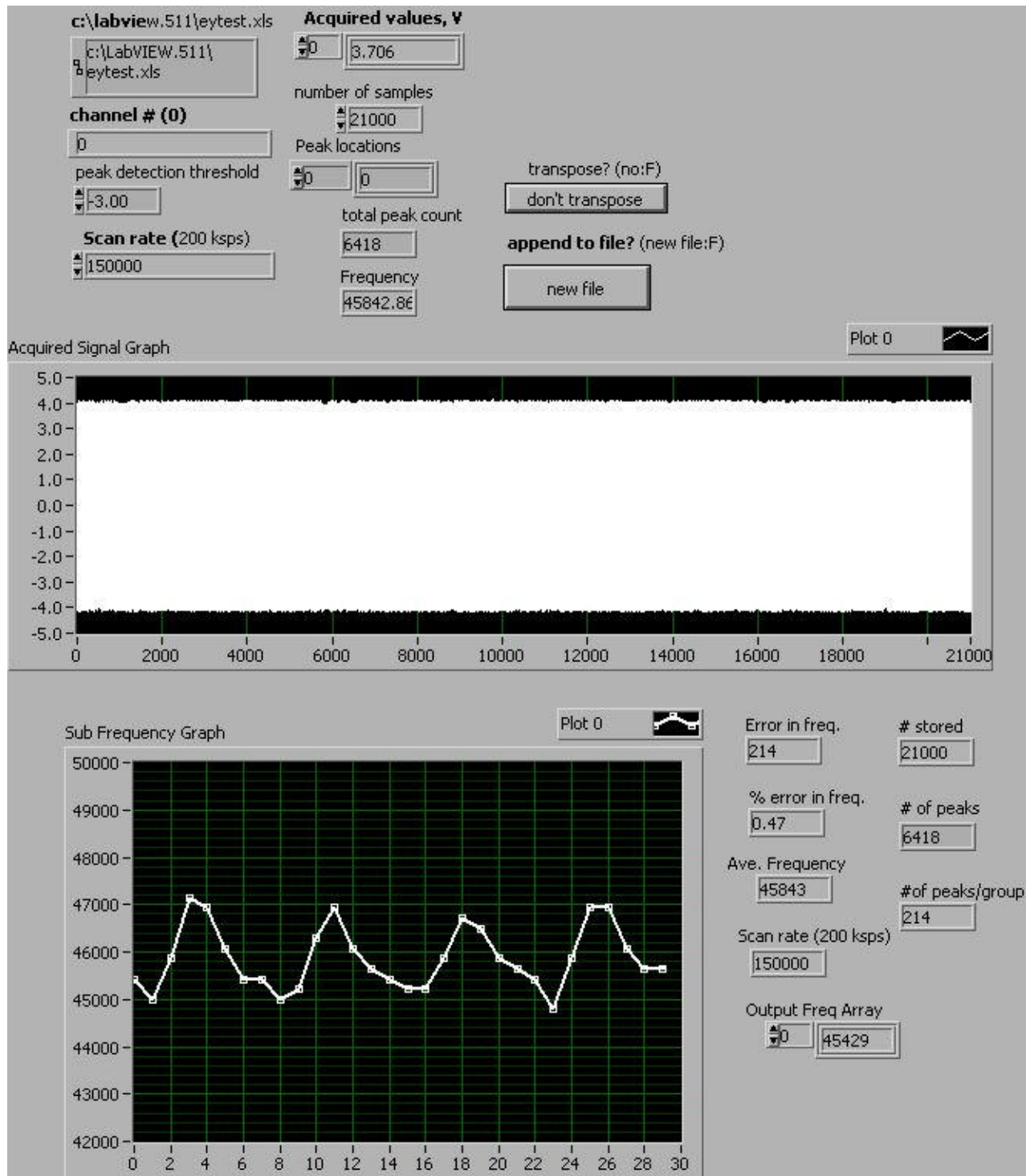
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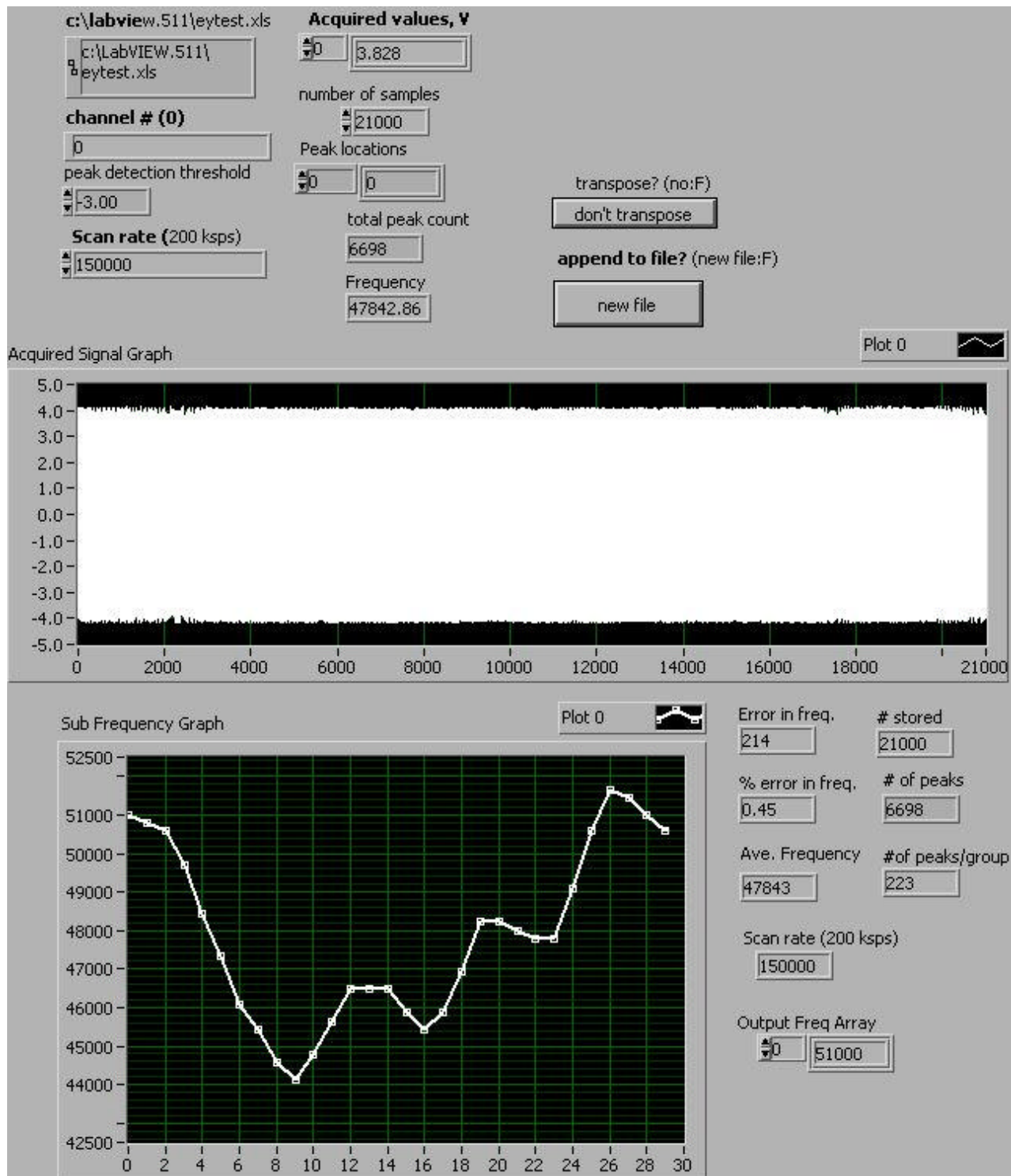**Figure 2. Front Panel of the Computer Program with Results of All Cylinders Firing.**

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Figure 3. Front Panel of the Computer Program with Results of Three Cylinders Firing.
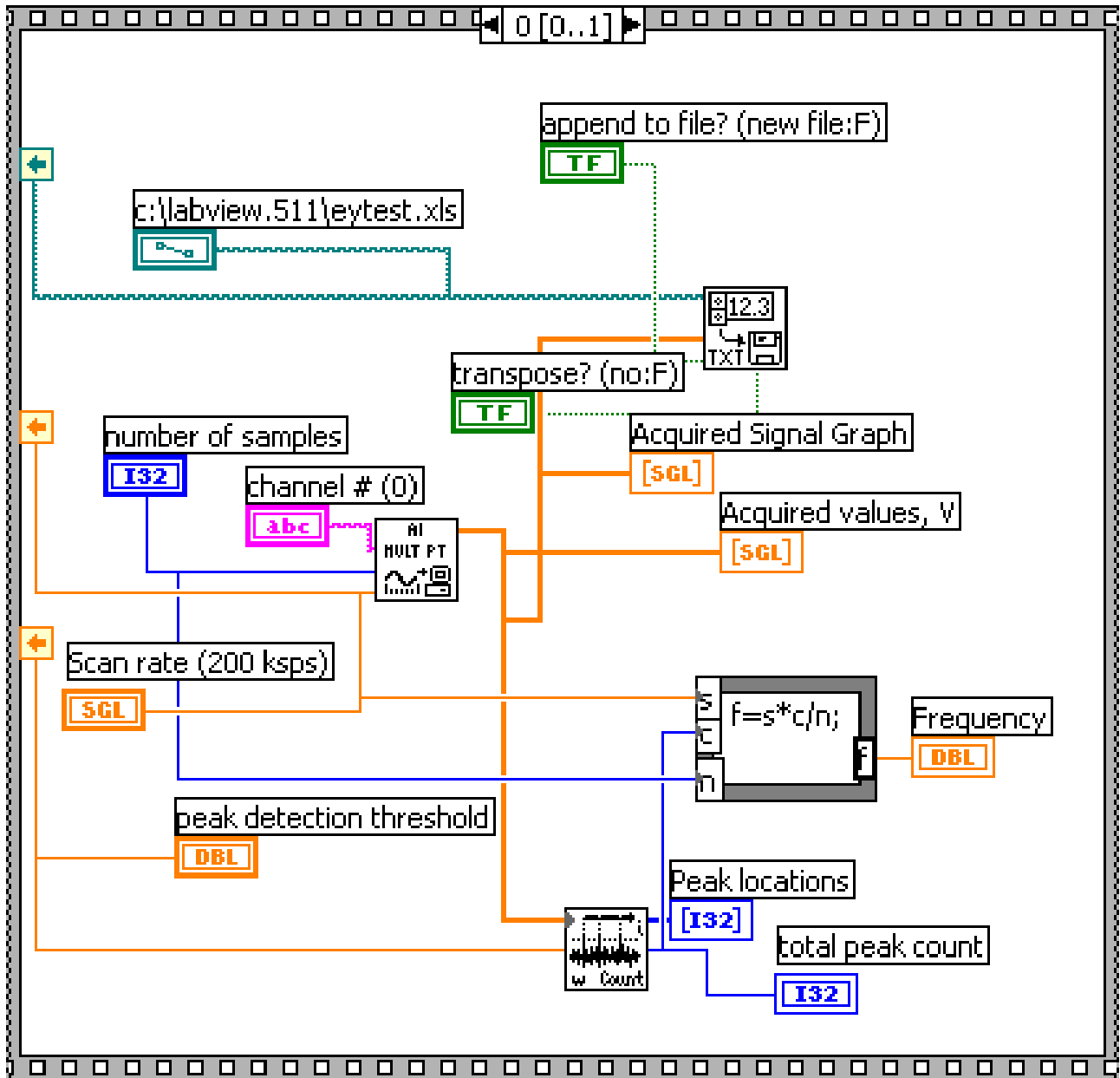
Figure 4. Block Diagram of the First Task of the Computer Program.
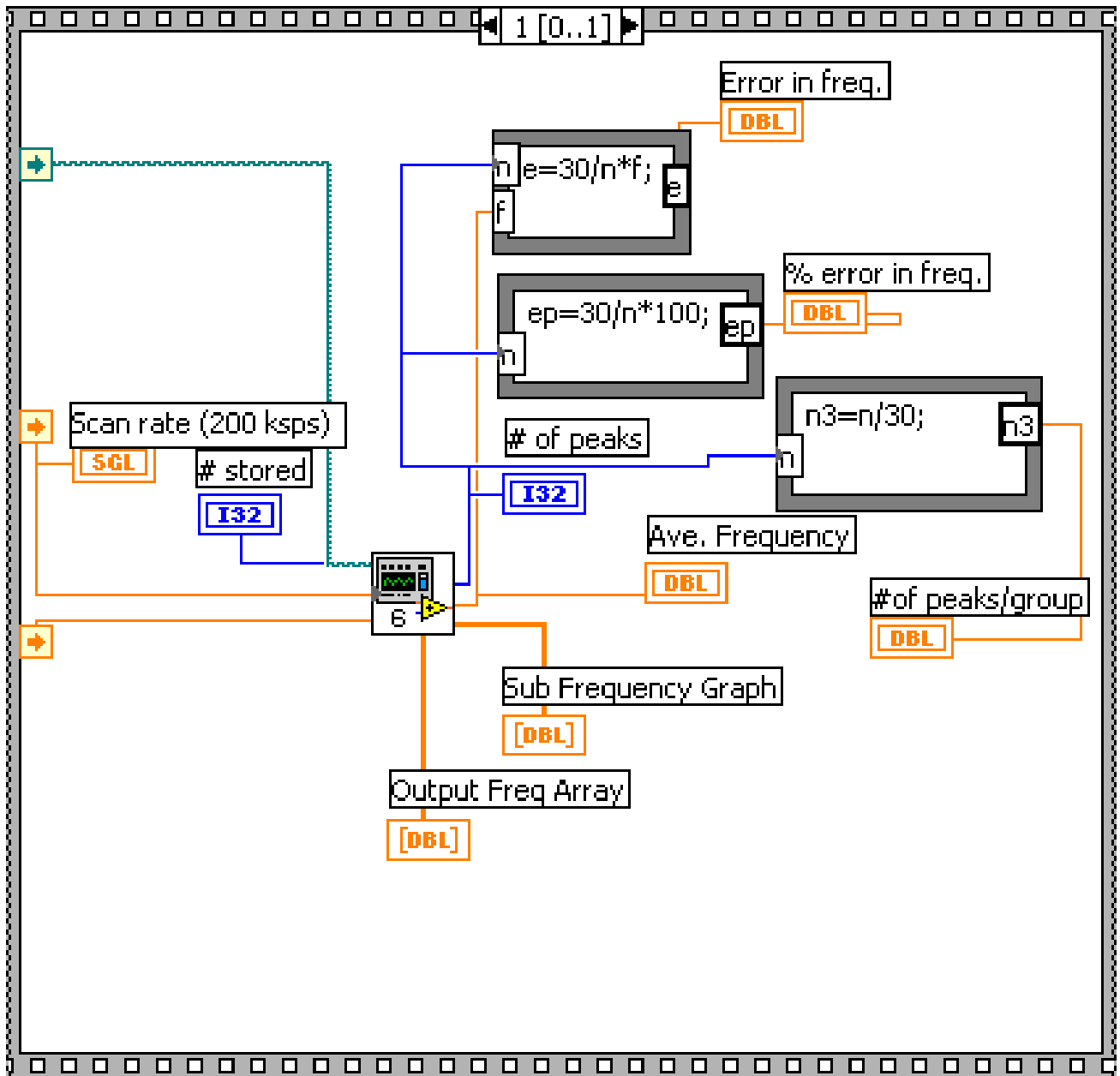
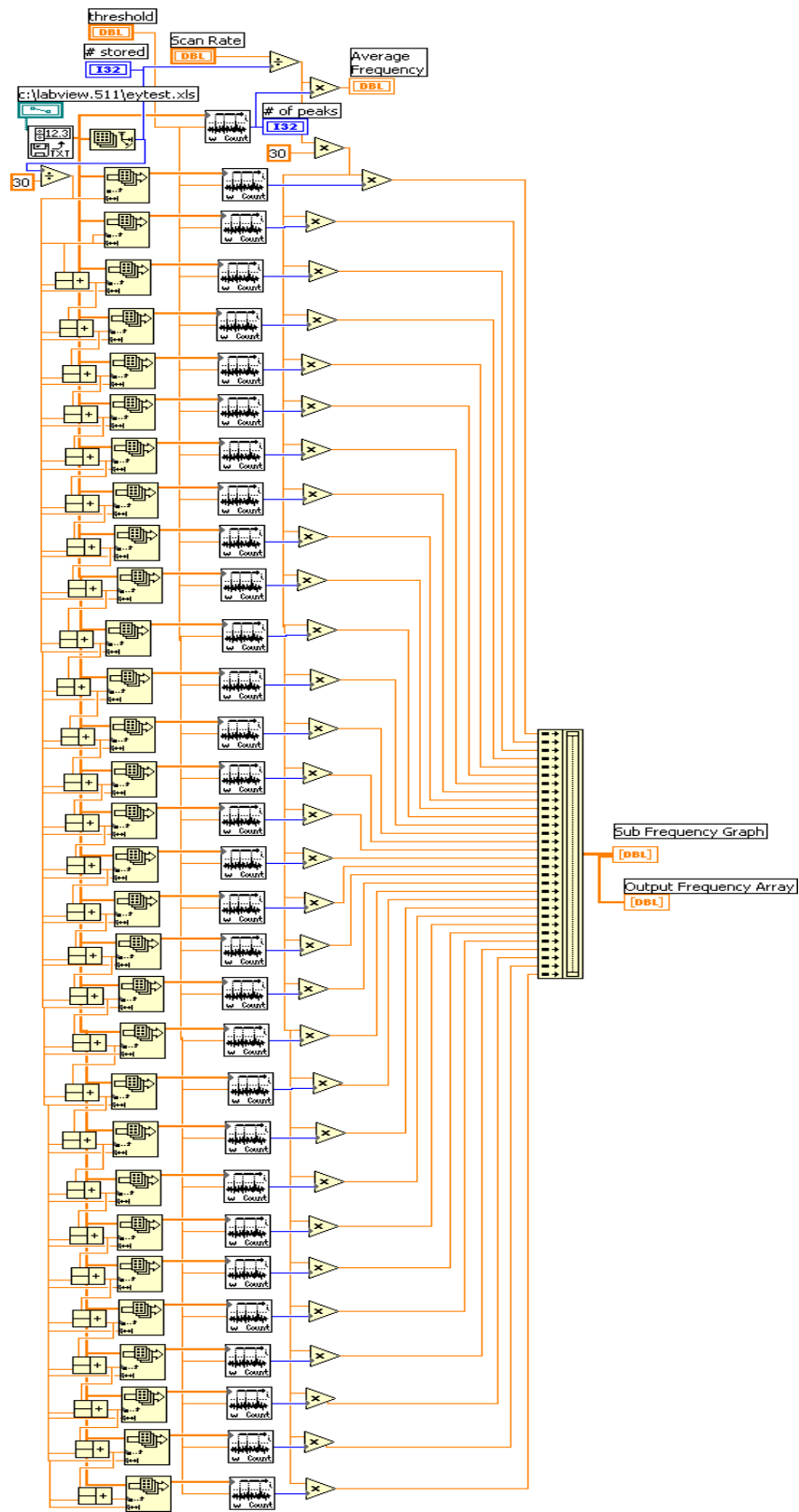**Figure 5. Block Diagram of the Second Task of the Computer Program**.

Figure 6. Center Block of the Second Task of Computer Program Expanded.