USING PERSONAL COMPUTER FOR VIBRATION MEASUREMENTS AND ROTOR BALANCING

Roshen Tariq Ahmed
Assistance Lecturer

Ayad Mahmoud Salman
Assistance Lecturer

Waleed Khalid Ibrahem
Assistance Lecturer

Energy and Fuel Research Center
University Of Technology
Iraq-Baghdad

ABSTRACT

Most prime movers have vibrational problems due to the inherent unbalance in the engines. The unbalance may be due to faulty design or poor manufacture. Naturally, the structures designed to support heavy centrifugal machines, like motors, turbines and reciprocating pumps, are also subjected to vibration. In all these situations, the structure or machine component subject to vibration can fail because of material fatigue resulting from the cyclic variation of the induced stress. Furthermore, the vibration causes more rapid wear of machine parts such as bearings and gears and also creates excessive noise.

This research is an example in the field of reducing as much as possible the vibration. To accomplish this, a digital instrument, based on an industrial computer, designed to measure the vibration level and rotor speed. Thereafter, displaying the required amount of weight that must be added or removed from blade in order to reduce the unbalance, which cause vibration

KEY WORD: Vibration control, Helicopter Vibration, Vibration Measurement, Rotor Balance.

الخلاصة

معظم الأجزاء المتحركة تعاني من مشاكل الاهتزازات بسبب عدم توازن أجزاء المحرك, أن عدم التوازن قد يكون بسبب أخطاء تصميميه أو أخطاء في الصناعة, فمثلا عدم التوازن في محركات الديزل تودي إلى تولد اهتزازات في أرضيه المحرك كافيه بدرجه تودي إلى حدوث أصوات في المنطقة المجاورة لها. أن محركات الطرد المركزي الثقيلة (ذوات الأجزاء الدوارة) كالمحركات والتوربينات كلها تعاني من الاهتزازات. وأن هذه الاهتزازات سوف تودي بالتالي إلى انخفاض كفاءة عمل المحركات و تقليل أعمارها.
أن فكره البحث هو قياس فرق الطور بين موجتين أحداهما من متحسس السرعة و الأخر من متحسس الاهتزازات، يتم حساب فرق الطور هذا بواسطة برنامج داخل الحاسوب بعد آن يتم إدخال الإشارتين إلى الحاسبة بواسطة دائرة تعشيق خاصة، آن البحث هو مثال في مجال تقليل الاهتزازات إلى اقل حد ممكن للمكائن ذوات الأجزاء الدوارة.

INTRODUCTION

One of the most important applications of vibration analysis is the solution of balancing problems. An unbalanced propeller, rotor or driveshaft will cause vibration and stress in the rotating part and in its supporting structure. Balancing of a rotating part is therefore highly advisable in order to accomplish one or more of the following (Prop and Rotor Balancing 2001):

- Increase quality of ride.
- Minimize vibration.
- Minimize audible signal noises.
- Minimize structural stresses.
- Minimize operator annoyance and fatigue.
- Increase bearing life.

Before attempting to balance the rotating parts of a unit, one may determine the possible sources of vibration and unbalance (Facilities Instructions Standards and Techniques 2002).

- Mechanical vibration sources.
- Electrical sources of vibration.
- The hydraulic passages of the unit should be checked for.

The aim of the work is to design and implement a computerized system to balance any rotating machine. The system must specify which blade on the rotor causes the unbalance condition and the amount of weight that must be added to the blades in order to balance the rotor.

It can be seen that if a rotating disc, see Fig. 1, is perfectly balanced, no vibration will be imparted to the supporting structure. If one adds a weight to the edge of the disc, the supports will be forced up and down once per revolution, as the disc rotates, generating a one-per-rev vibration. For simplicity, let us visualize that the supporting structure is in its farthest up position when the weight on the edge of the disc is up. If the weight on the edge of the disc is moved to a new location, it is clear that the support will still be up when the weight is up, as in the first instance. It follows that wherever the weight is fixed, the motion of the support will be “maximum up” when the heavy side of the disc is at the top of its rotation.

Now, starting with an unbalance disc, if one can determine the angular position of the disc when the support is “maximum up”, it should be able to balance the disc. Simply stop the disc, position it was observed, and a weight is added to the bottom (Clarence W. de Silva 1999).

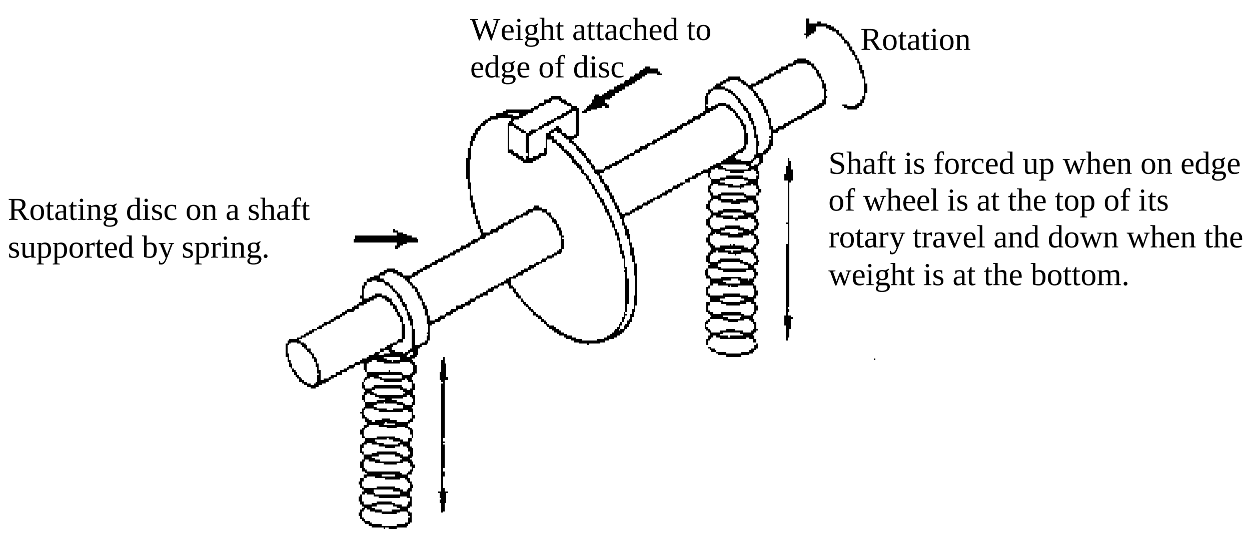


Fig. 1 Rotating of unbalance disc.

PRINCIPLE OF OPERATION

The basic principle of the suggested balancing system operation is depending on measuring phase difference between two signals. By using two sensors. One is the magnetic pickup, which gives the pulses per revolution, and these pulses will be the reference for all calculations and measurement. The second sensor is the accelerometer, which give signals corresponding to vibration level. The block diagram of the implemented system is shown below.

The magnetic pickup signal was converted to square waveform using appropriate circuit. This square wave will be sensed by a personal computer using an interface circuit.

Meanwhile accelerometer signals was filtered, smoothed and amplified by using an electronic circuit.

Magnetic pickup and the accelerometer signals are in an analog form converted to digital form by the interface card. The two digital signals then fed to the computer for later signal processing. Inside the computer, the Revolution Per Minute (RPM) will be measured from the magnetic pickup, and from the RPM the frequency can be measured which is used as the center frequency for the BandPass Filter (BPF). The accelerometer signal is representative of all the mechanical motion (vibration) of the point to which it is attached. To derive a useful signal, all of the signals except that from the one per revolution of the rotor being worked must be rejected. The bandpass filter passes only the signal at the working RPM, which is the center frequency of the BPF.

The output signal from the BPF is then converted to square wave in order to measure the phase difference between these signals. This phase indicates an angle between (0°-360°). The amount of vibration (amplitude) is measured from the output signal of the accelerometer.

After that the additive weights which assigned from the pervious measurements must be added in order to reduce the vibration depend on charts supplied by the manufacturer of the machine. Fig. 2 shows the complete block diagram of the system.

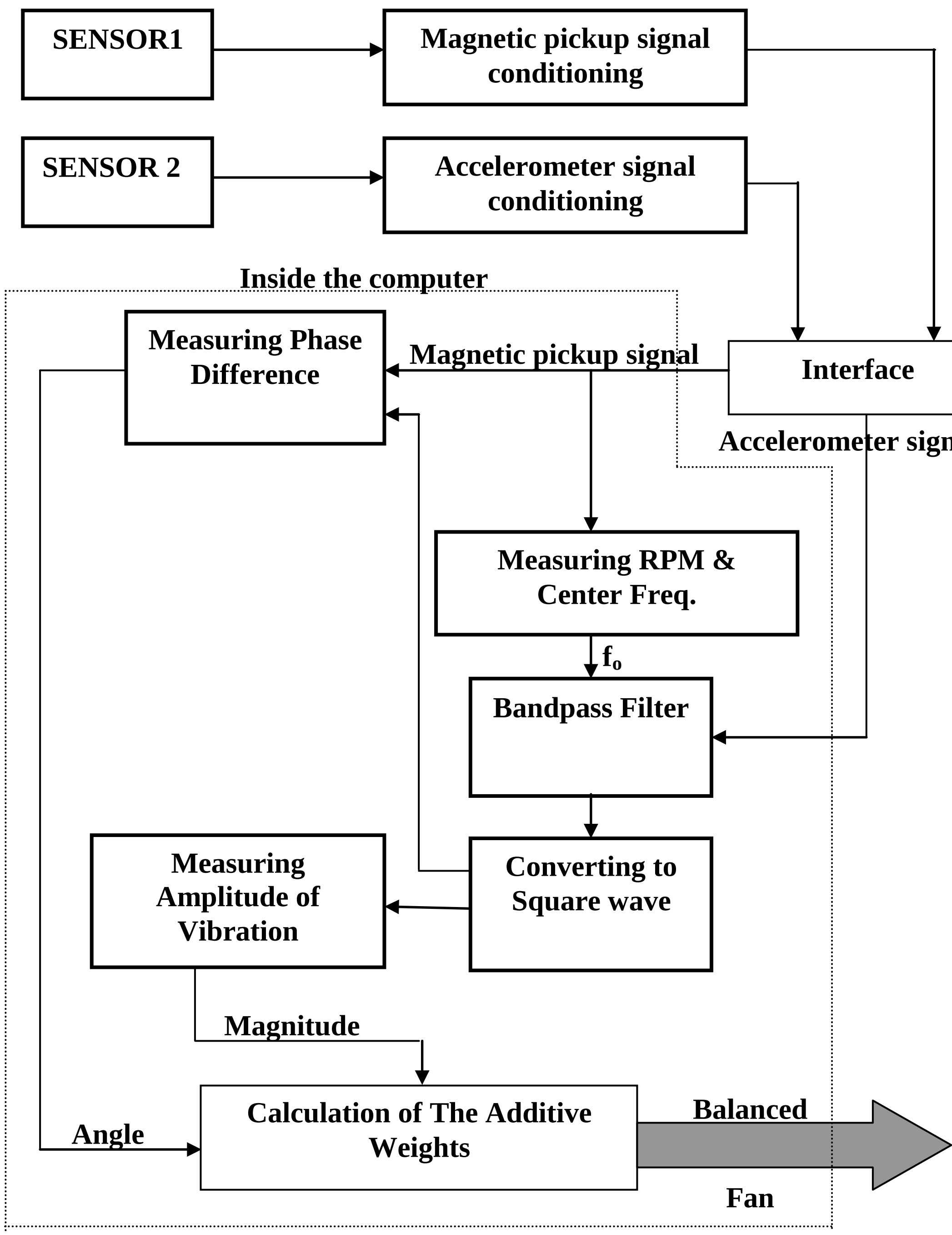


Fig. 2 Block diagram of the complete system.

TRANSDUCER USED IN THIS WORK

The two transducers used in this project are magnetic pickup for speed measurements and accelerometer for vibration measurements.

THE MAGNETIC PICKUP

The first transducer is the magnetic pickup, which is used to measure the speed of rotation (RPM). The principle of operation is very simple and depends on (Faradays law), it consist of a permanent magnet and coil, when a piece of metal moves in its magnetic field it cuts the magnetic flux and generate a pulse just like the principle of generators. The magnetic pickup is fixed on the fixed plate (unrotating part) while a piece of metal (target) is fixed on the rotating part of the rotor. The target must be small and light as possible. When the rotor began to rotate, the target cut the magnetic field and generates a signal on the output of the magnetic pickup. The distance or air gap between the target and the magnetic pickup is between (0.5 – 2) mm and it depends on the type of magnetic pickup used.

Amplitude of the output signal depend on speed of rotation (speed at which the target cut the magnetic flux), air gap, size and the shape of target itself (Chadwick-Helmuth 1981). The magnetic pickup used has the specification that its operating temperature ranges (-10 to +120 °C), mass 380 gram, inductance 115 mH, DC resistance (220 to 260) Ω at 25 °C (Magnetic Pickup & In-Line Preamplifier) . The detected frequency in Hz is obtained from the relation:

$$f = \frac{RE}{60} \qquad (1)$$

Where f = Detected frequency in Hz.

R = Number of revolution (RPM).

E = Number of targets.

Fig. 14 is a result of a test with RPM=160 and sampling time equal to 1 milliseconds with target one is closer than target two to the sensor.

And finally the fig. 3A and fig. 3B below shows the magnetic pickup external and internal construction (Maurice L. Adams 2000).

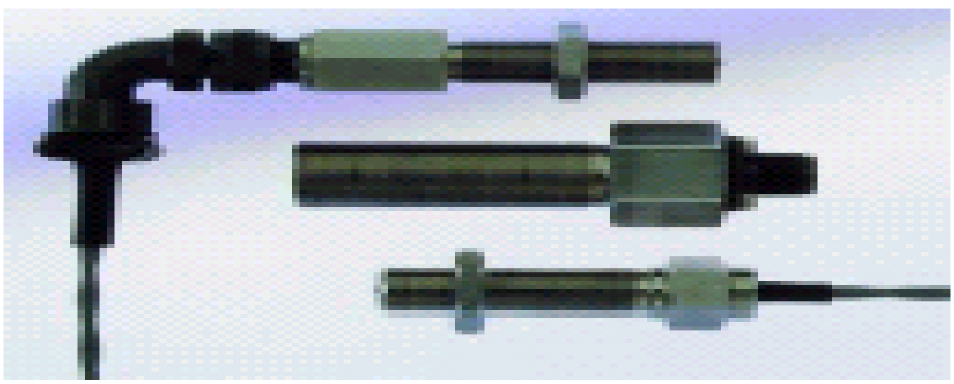


Fig. 3(A) External construction of the magnetic pickup.

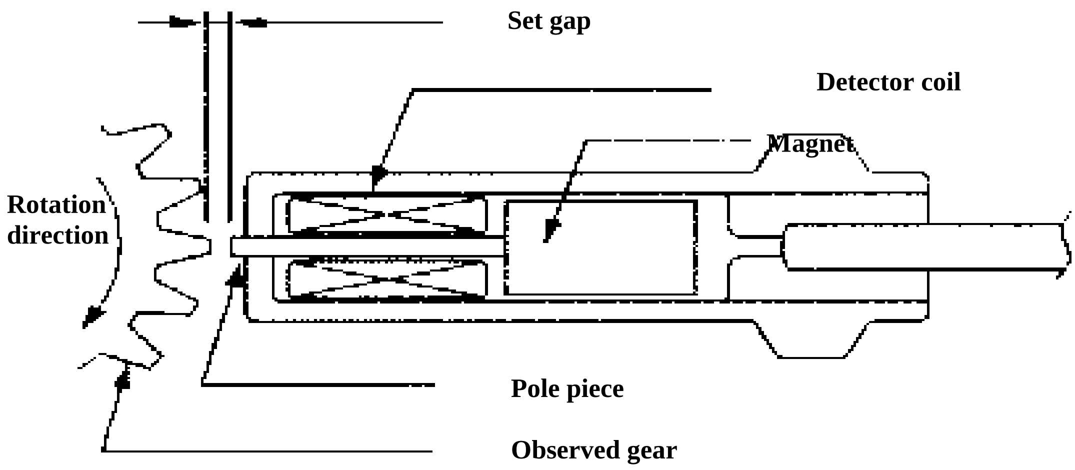


Fig. 3(B) External construction of the magnetic pickup.

MAGNETIC PICKUP SIGNAL CONDITIONING CIRCUIT

The magnetic pickup signal must be converted to square waveform using appropriate electronic circuit. This square wave will be sensed by a personal computer using a suitable interface circuit.

A suitable circuit will convert the signal from the magnetic pickup to a square wave. Fig. 4(A) and fig. 4(B) shows the circuit diagram and a simplified block diagram for the circuit used. The first block is a low pass filter, which pass the required signal frequency from magnetic pickup.

The second block is a comparator, in order to convert the sine wave to square wave, and the output signal of the second part is shown in Fig. 15. In order to get a pure square wave with 50% duty cycle the third block is added, which is a J-K flip flop. Because of using JK flip-flop output signal frequency of the overall circuit will be half frequency of the system-input signal as shown in Fig. 16. This problem will be solved in the program (software). Magnetic pickup signal is in an analog form converted to digital form by the interface card. The signal then fed to the computer for later signal processing. Inside the computer, the Revolution Per Minute (RPM) will be measured from the magnetic pickup (Chadwick-Helmuth 1981).

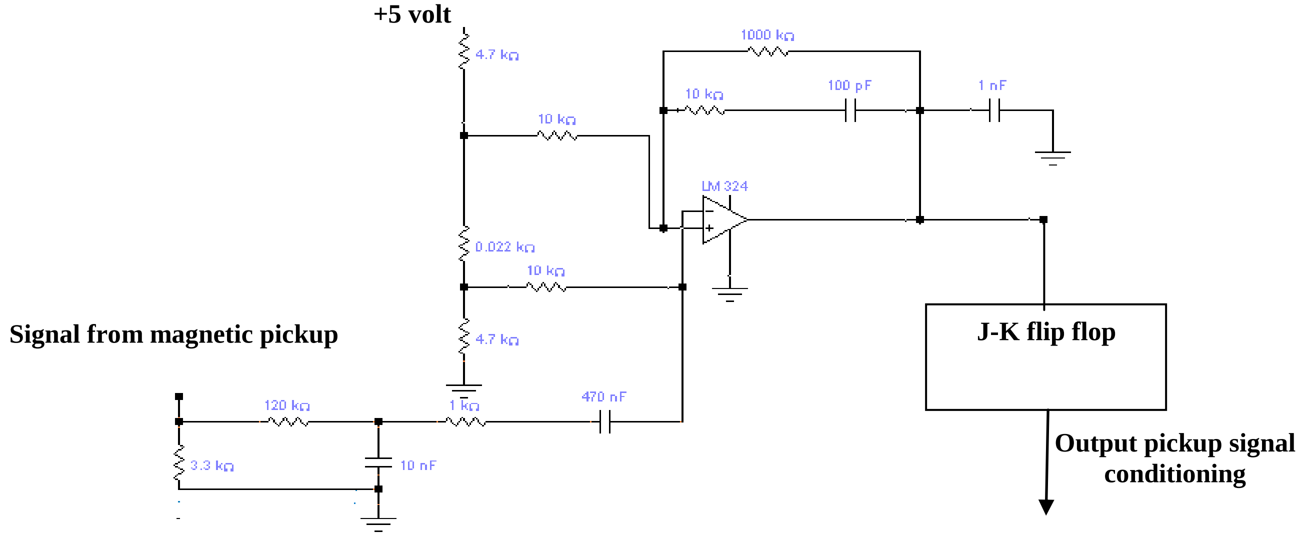


Fig. 4(A) Circuit diagram for magnetic pickup signal conditioning.

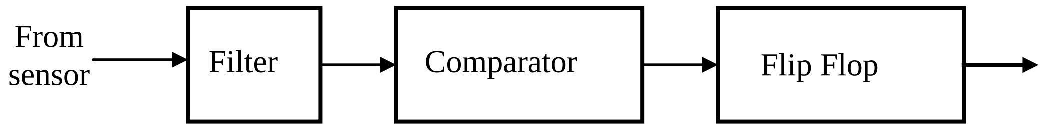


Fig. 4(B) Magnetic pickup signal conditioning block diagram.

The above electronic circuit is very easy, simple, components are available in markets and over all its operation is very efficiency with low maintenance.

THE ACCELEROMETER

The second transducer is the accelerometer, which provides the balancer with an electrical representation of the physical motion of the point to which it is attached.

Fig. 17 shows the accelerometer output signal. Notice that the output signal is a combination of various signals with different frequencies. This is because the accelerometer is very high sensitive device and there are many other vibration sources acts on the point to which the accelerometer is attached such as shafts, gears, and other rotating parts (S. Q. Reza Moheimani and Andrew J. Fleming 2006) and (Maged Mostafa Alaa El Din Sayed 2006).

ACCELEROMETER SIGNAL CONDITIONING CIRCUIT

In Fig. 5 shows the circuit diagram related to the accelerometer (Chadwick-Helmuth 1981). Fig. 6 shows a simplified block diagram of Fig. 5.

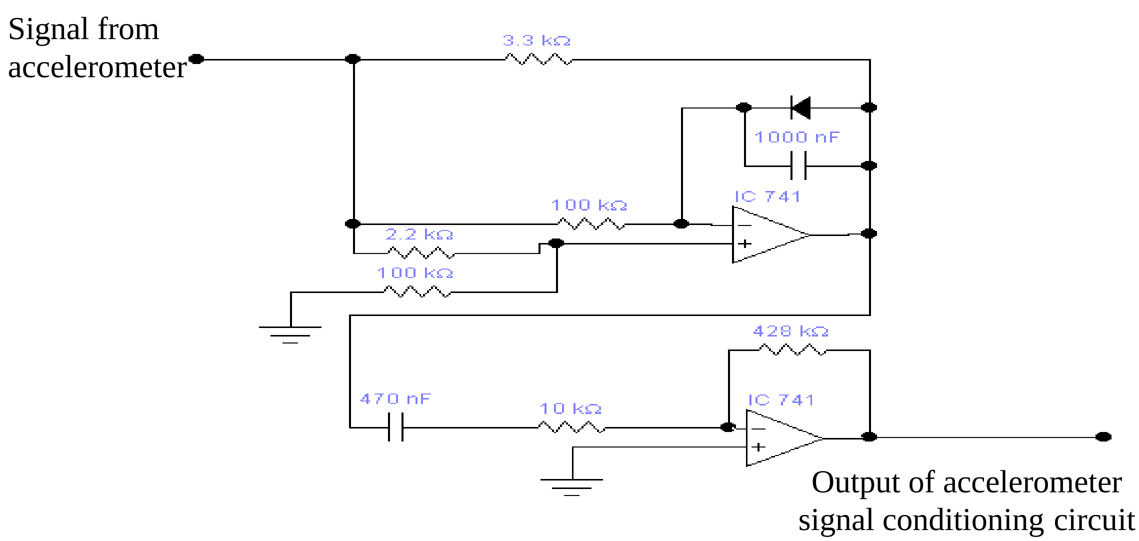


Fig. 5 Accelerometer signal conditioning circuit diagram.

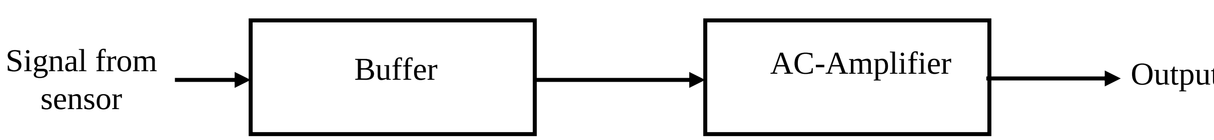


Fig. 6 Accelerometer signal conditioning circuit block diagram.

The accelerometer signal is very small (millivolts) with dc components, therefore an AC-amplifier is used to amplify the signal. In order to do this the second part of the circuit is used which removes all dc components, and amplifies the input signal. Because of using inverting amplifier this part will change the polarity of signal to its original polarity. Fig. 18 shows the output signal of the second part. Fig. 19 shows difference between accelerometer signal before and after amplification.

THE INTERFACE CARD

The output signal from the magnetic pickup and the accelerometer are in analog form. In order to feed these signals to a digital computer, a suitable interface card designed. The interface card contain analog to digital converter (ADC), ADC are widely used for data acquisition.

Digital computers use discrete values, but in the physical world everything is continues (analog) such as temperature, pressure and velocity etc.

The 0804 IC is an ADC it works with (+5 volt) and has a resolution of 8 bits. The sampling rate can be controlled by these 8 bits with clock frequency 1.16 microseconds and connected to the parallel port. The language of programming is written in visual basic. The complete flow chart of the interface card is shown in fig. 7 (Sood 1990) and (User's Manual 1995).

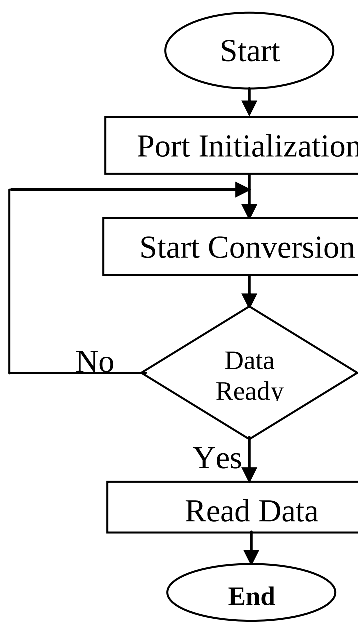


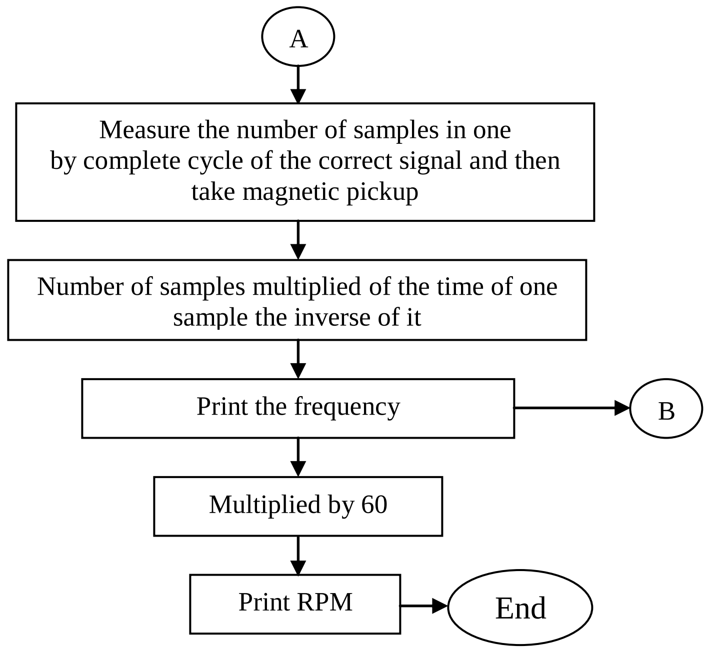
Fig. 7 Complete flow chart of the interface card.

THE SOFTWARE

Till now the hardware feeds the computer with magnetic pickup signal (square wave) and the amplified accelerometer signal. Principle of operation is to measure the phase difference between these two signals and to measure the amplitude of vibration.

In order to measure the phase difference between these two signals they must be of the same form (square wave) and same frequency. Therefore the accelerometer signal must be converted to square wave. Before doing this, the signal must be filtered, because the accelerometer signal is a combination of many signals with different frequencies as was shown in Fig. 18, so the accelerometer signal must be filtered from all these undesirable signals except the signal with rotation frequency (Michael R. hatch 2000) and (Nian-Zhao Jiang et. al. 2007)

Step one: Frequency and speed measurement, Figure below shows the flow chart of this part of the software



Step two : Filtering the accelerometer signal

The heart of the Balancer is its tunable electronic band pass filter. The accelerometer generates an electrical signal which is representative of all the mechanical motion (vibration) of the point to which it is attached other than one-per-revolution of concern, such as shafts, gears, engines, bearings, all will contribute their own vibrations. The accelerometer is “a high fi” device and reads all the vibration presents at the point to which it is attached to derive a useful signal, all of the signal except that from the one-per-revolution of the rotor being worked, must be rejected (Moschytz and Horn 1981).

Filters, often called wave filters, are frequency-selective networks designed to ‘pass’ or transmit sinusoidal waves in one or more continues frequency bands and to ‘stop’ or reject sinusoidal waves in the complementary bands. Filters with single pass band are typically classified as low pass, high pass, and band pass, depending on the band of frequency, which are passed. For example, the pass band of the band pass filter illustrated in Fig. 8(A) extends from the frequency ω_1 to ω_2.

A band pass filter is a circuit that permits the passage of frequency components of a signal over a frequency band and rejects all other frequency components of the signal. A filter can be built by using, for example, resistors, inductors, and capacitors. Fig. 8(B) illustrates the response characteristics of a Band pass filter whose lower and upper cutoff frequencies are fL and fH, respectively. A practical filter will have a response characteristic deviation from the ideal rectangle as shown by the solid line in Fig. 8(B). For a good band pass filter, the ripples within the band will be minimum and the slopes of the filter skirts will be steep to maintain the actual band pass close to the ideal value the bandwidth is BW = fH - fL . For a practical filter, the frequencies fL and fH at which the response is 3 db below its mean band pass response are called the cutoff frequency (Bogner and Constantinides 1980).

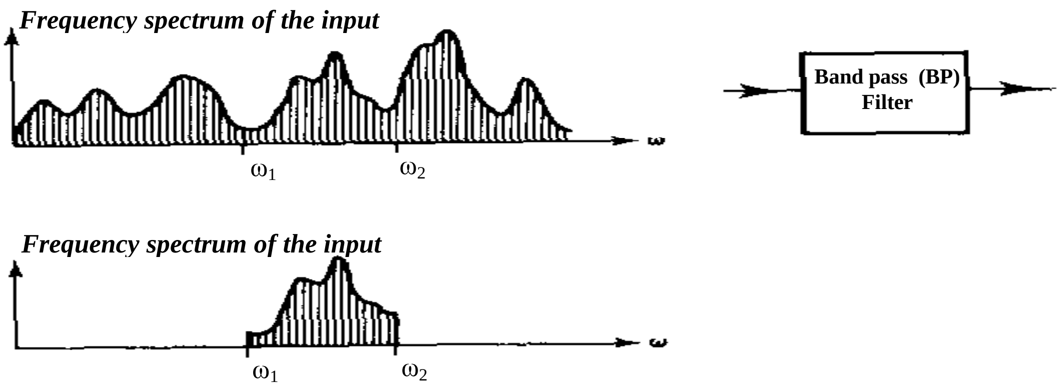


Fig. 8(A) Typical input and output frequency spectrum of band pass filter.

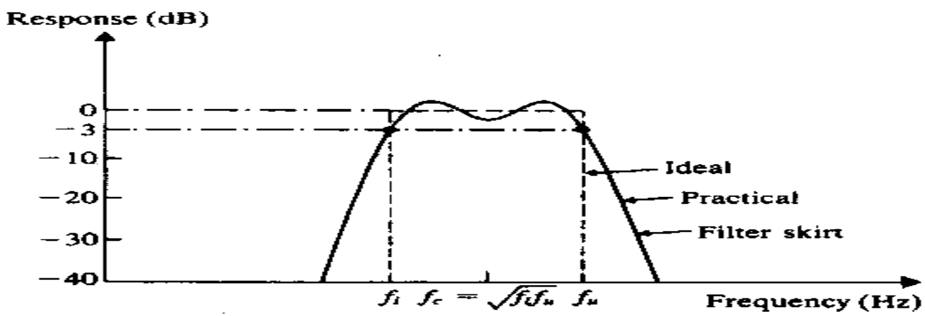


Fig. 8(B) Response of a Band pass filter.

The frequency obtained in the previous part is used as the center frequency of the bandpass filter. The bandpass filter is a Butterworth digital bandpass filter and used to pass only the frequency corresponds to the one-per-revolution (Bogner and Constantinides 1980).

Since the software do the work of the filter so it is digital filter used. The digital filter transfer function is derived by Z-transforming the transfer function of a known analogue filter G(s), that is G(z)=Z|G(s)|

In general

$$G(z) = \frac{a_0 + a_1 Z^{-1} + a_2 Z^{-2} + \cdots + a_p Z^{-p}}{1 + b_1 Z^{-1} + b_2 Z^{-2} + \cdots + b_J Z^{-q}} = \frac{Y(z)}{X(z)}$$

Where ai $(0 \le i \le p)$ and bj $(1 \le j \le q)$ are the digital filter coefficients. It follows that:

$$X(z)[a_0 + a_1 Z^{-1} + a_2 Z^{-2} + \cdots + a_p Z^{-p}] = Y(z)[1 + b_1 Z^{-1} + b_2 Z^{-2} + \cdots + b_q Z^{-q}]$$

i.e.
$$a_0 X(z) + a_1 X(z) Z^{-1} + a_2 X(z) Z^{-2} + \cdots + a_p X(z) Z^{-p}$$
$$= Y(z) + b_1 Y(z) Z^{-1} + b_2 Y(z) Z^{-2} + \cdots + a_q Y(z) Z^{-q} \qquad (2)$$

But Z-k corresponds to a delay equal to k sampling periods, consequently eq. (2) may be written in a linear difference equation form:

$$a_0 x_K + a_1 x_{k-1} + a_2 x_{k-2} + \cdots + a_p x_{k-p} = y_k + b_1 y_{k-1} + b_2 y_{k-2} + \cdots + b_q y_{k-q}$$

$$\therefore y_k = a_0 x_k + a_1 x_{k-1} + a_2 x_{k-2} + \cdots + a_p x_{k-p} - b_1 y_{k-1} - b_2 y_{k-2} - \cdots - b_q y_{k-q} \qquad (3)$$

Eq. (3) is recursive, whereby the present output sample value y_k is computed using a scaled version of the present input sample x_k and scaled versions of previous input and output samples. This form corresponds to an Infinite Impulse Response (IIR) digital filter. Sometimes it is useful to represent the linear difference equation in a block diagram form, as shown in Fig. 9 (Bogner and Constantinides 1980).

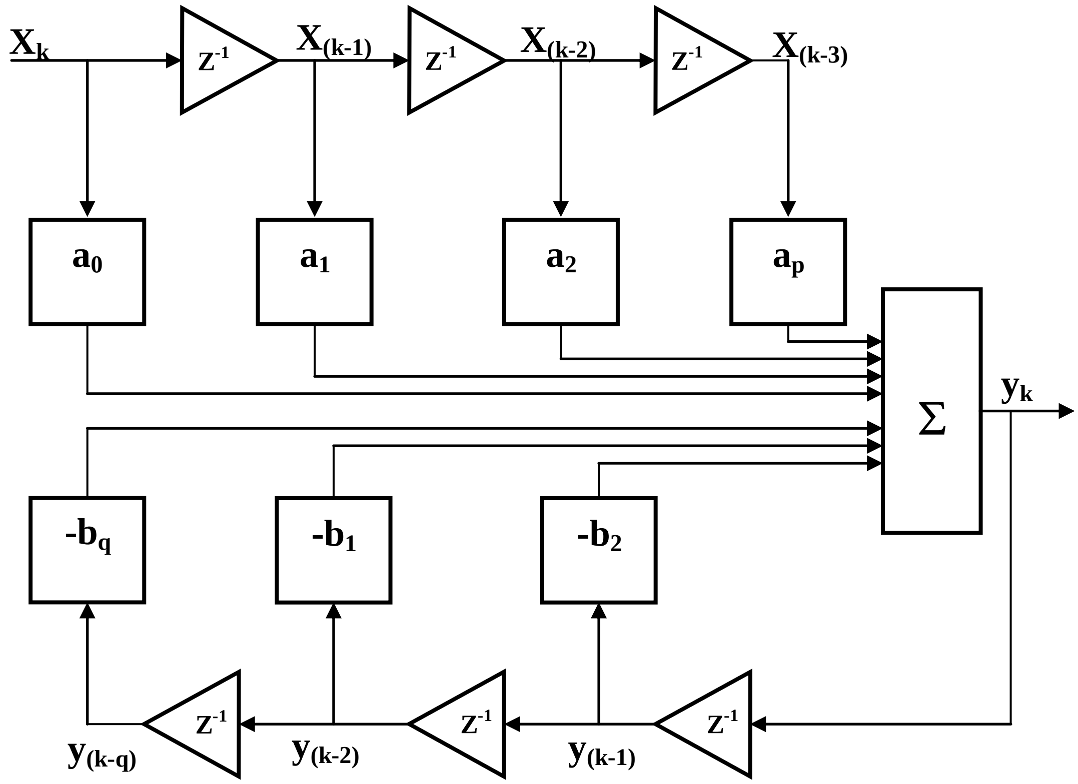
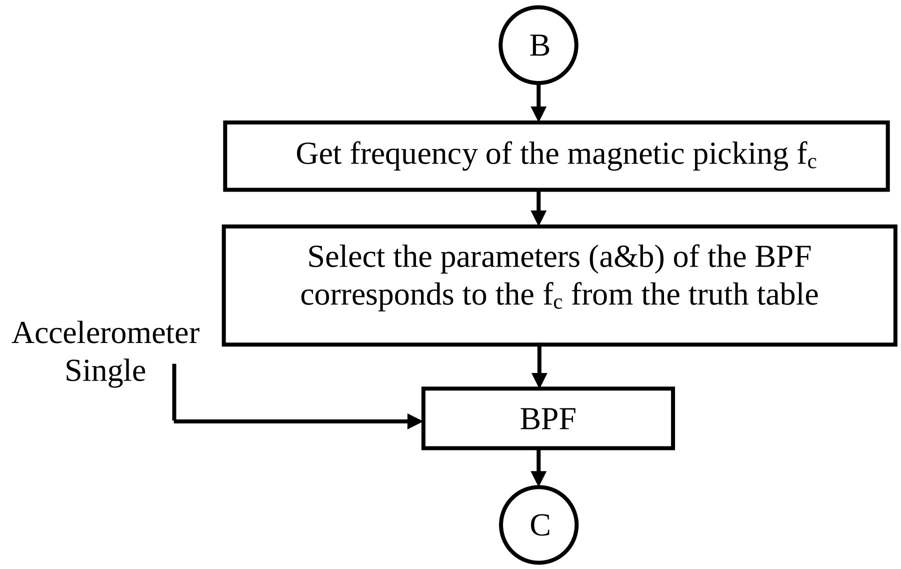


Fig. 9 Block diagram of IIR digital filter.

Butterworth is used because of its good properties such as fast response with fewer ripples. Fig. 10 shows the Butterworth bandpass filter output when it is applied to the accelerometer signal.

Because of different speeds (RPM) of different machines, the center frequency is varied. The bandpass filter used is designed to be general one (i.e. for different speeds). Therefore it is suitable for different frequencies and this is done by obtaining the parameters of the bandpass for each speed (center frequency) (E. F. Berkman and E. K. Bender 1997).

The software measures the RPM and according to that, it will select the appropriate parameter, from a look up table parameter order to get the correct filter. This table is obtained by using Matlab programming (Bogner and Constantinides 1980). The aim of this filtering is to get accelerometer signal frequency equivalent to magnetic pickup signal frequency in order to measure the phase shift.



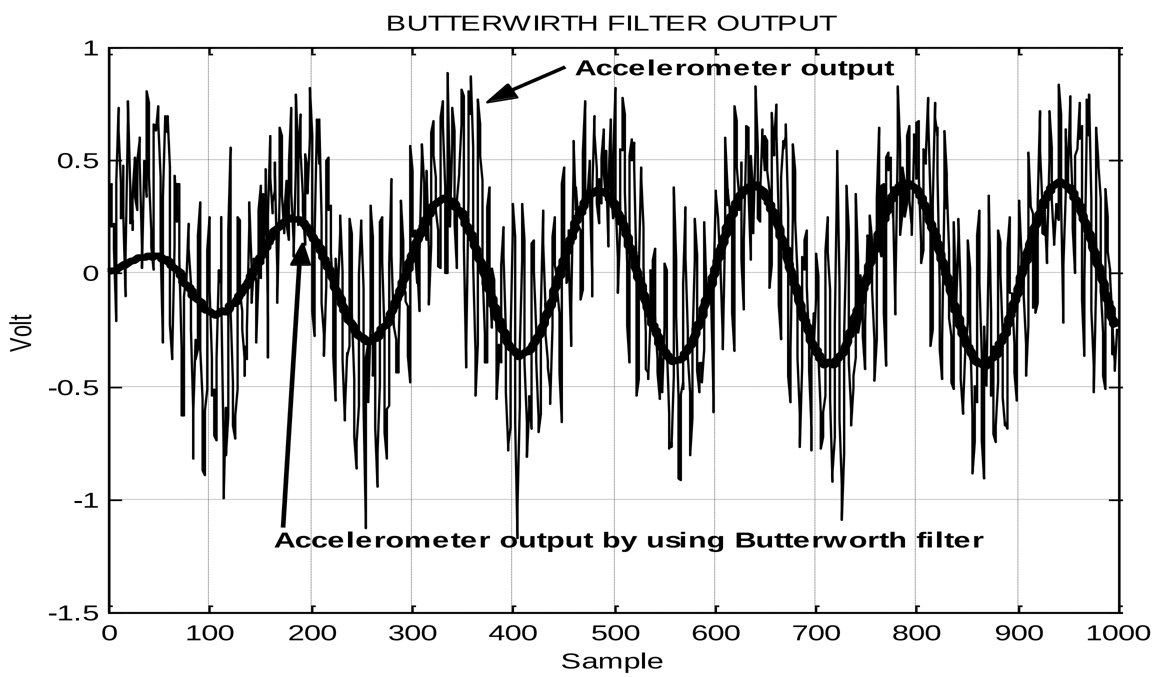
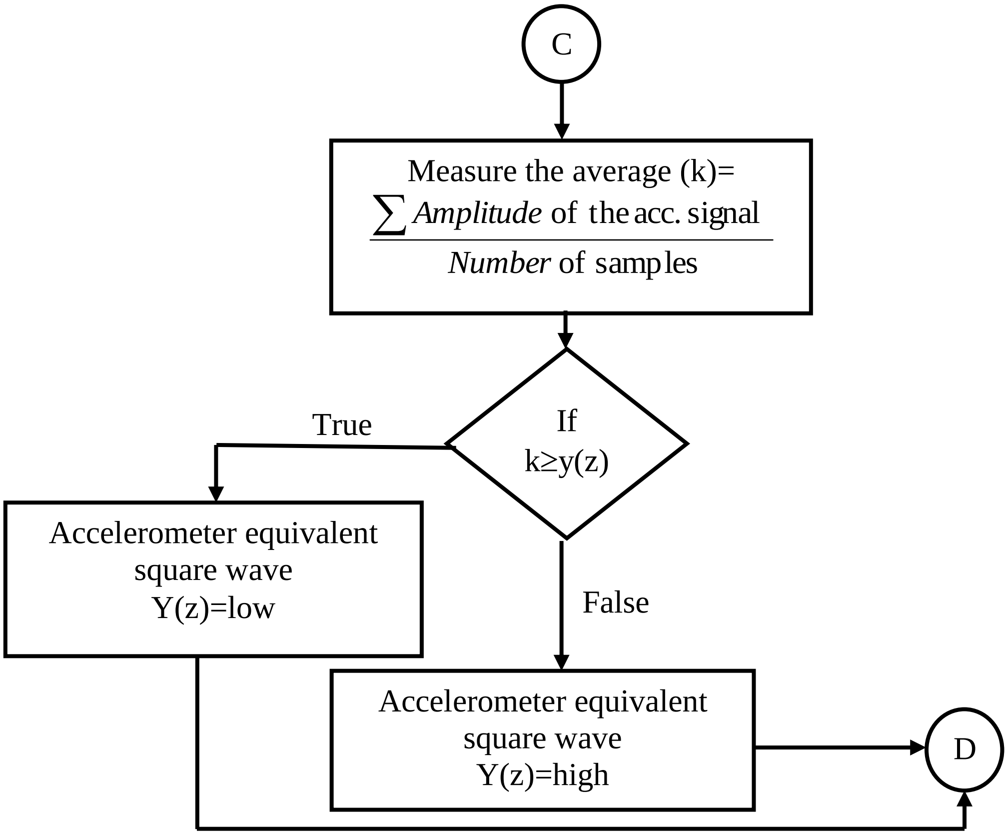
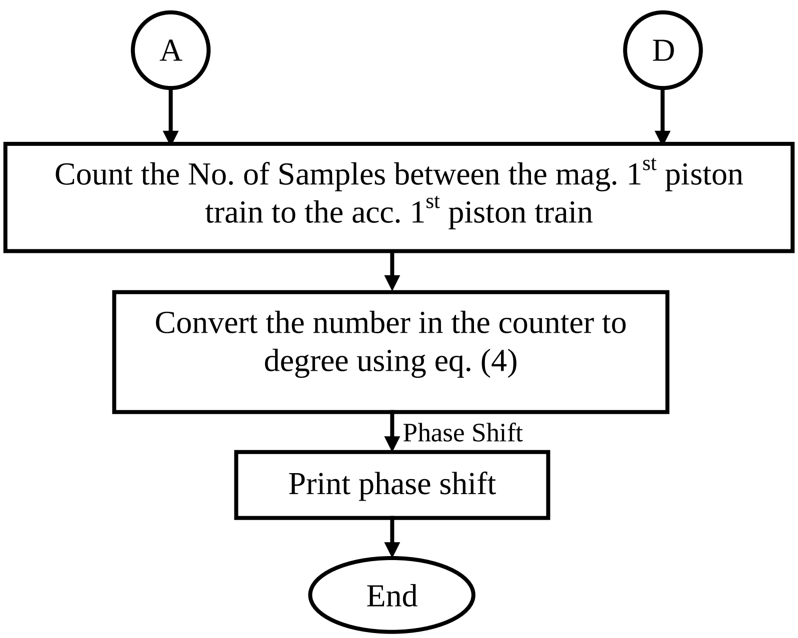


Fig. 10 Butterworth bandpass filter output for the accelerometer signal.

Step three : Accelerometer equivalent square wave

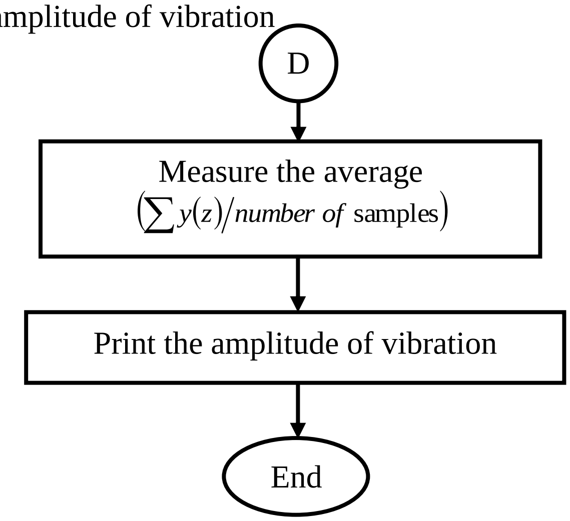


Step four : Phase shift measurement



$$Phaseshift\ (\deg ree) = \frac{Measured\ phase\ shift\ (in\ samples) \times 360}{Number\ of\ samples\ for\ one\ complete\ cycle} \quad (4)$$

Step five : Measuring the amplitude of vibration



Step six : Calculation of the additive weights

Until now the phase shift (degree or Clock angle) and amplitude (Volt) of vibration is obtained. The final part of the software is to calculate the additive weights for balancing. The manufacturer of each machines provides a certain chart for evaluating the amount of these weights.

The balance charts receives the measurement of vibration (amplitude and location of additive weight) and calculate the weights required for balance the rotor, These charts came from the calculations of the designer of the rotor machines (Peter Konstanzer et. al. 2008).

A balance chart consist of:

- A clock face (12 radial lines) representing "clock angle".
- A set of 10 concentric circles representing "Volt" , drawn over the clock face, with zero at the center and 1.0 at the outside.
- A graph over the clock face and "Volt" circles, whose axes are geometrically related to the available weight attachment points (as provided by the manufacturer). If the weight attachment points are 90^o apart (as on 4-blade rotor) the axes of the "graph" are at 90^o to each other. If for a 3-blade rotor, the axes are 120^o apart, etc.

The intersection of "Volt" circle and "clock angle" lines define a point on the chart. From this point, lines to the axes of the graph show amount and location of the weight to be added or subtracted required to accomplish balance.

Fig. 11 shows one sample of the charts used in main rotor of helicopters with 3-blade type (Gazelle).

example (1):

Vibration amplitude 0.65 volt and clock angle 1.33 there fore the additive weight for balance is 8 grams to the Target blade and 8 grams to the A blade.

example (2):

Vibration amplitude 0.85 volt and clock angle 5.5 there fore the additive weight for balance is 12 grams to the B blade blade and 10.5 grams to the target blade.

example (3):

Vibration amplitude 0.8 volt and clock angle 7.75 there fore the additive weight for balance is 4 grams to the A blade and 12 grams to the B blade.

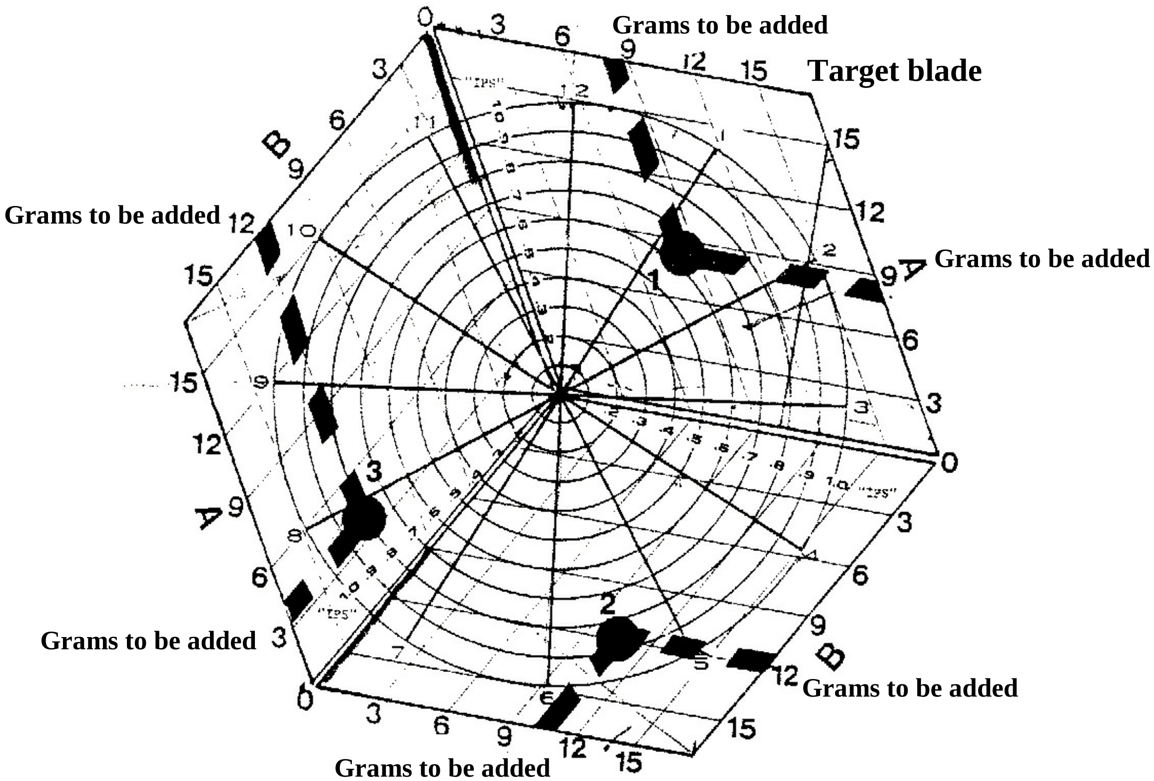


Fig. 11 Chart for three-blade rotor.

SIMULATOR

In order to test the designed balance system, i.e. the hardware and software, a simulator is needed. . The simulator consists of a DC motor operates from 12 volt with full load current about 8 Ampere. The speed of rotation can be varied from the DC power supply, which is designed specially for the simulator.

The motor maximum speed is 900 RPM (full load) and can be varied through a potentiometer on the output of the power supply. The motor is positioned vertically and fixed on metal plate, which can be used to hold the magnetic pickup and the accelerometer. This small metal plate is connected to the base of the simulator through three legs with springs to allow free movement of the motor when it is unbalance. There is a vertical shaft used to fix the motor so that it prevents the motor from any movement. This situation is useful for some measurements and tests when considering the motor to be completely balanced.

The motor has two shafts, the first one is upward and connected to a three-blades fan. Different weights can be fixed to the blades to control vibration. The second shaft is downward and with a small metal plate (Target) used to operate with the magnetic pickup.

The simulator is a general purpose one, so one can change the fan to another fan with different number of blades. Also one can change the number of targets to give more pulses per revolution (pinion) such application like turbine, the simulator is shown in fig. 12.

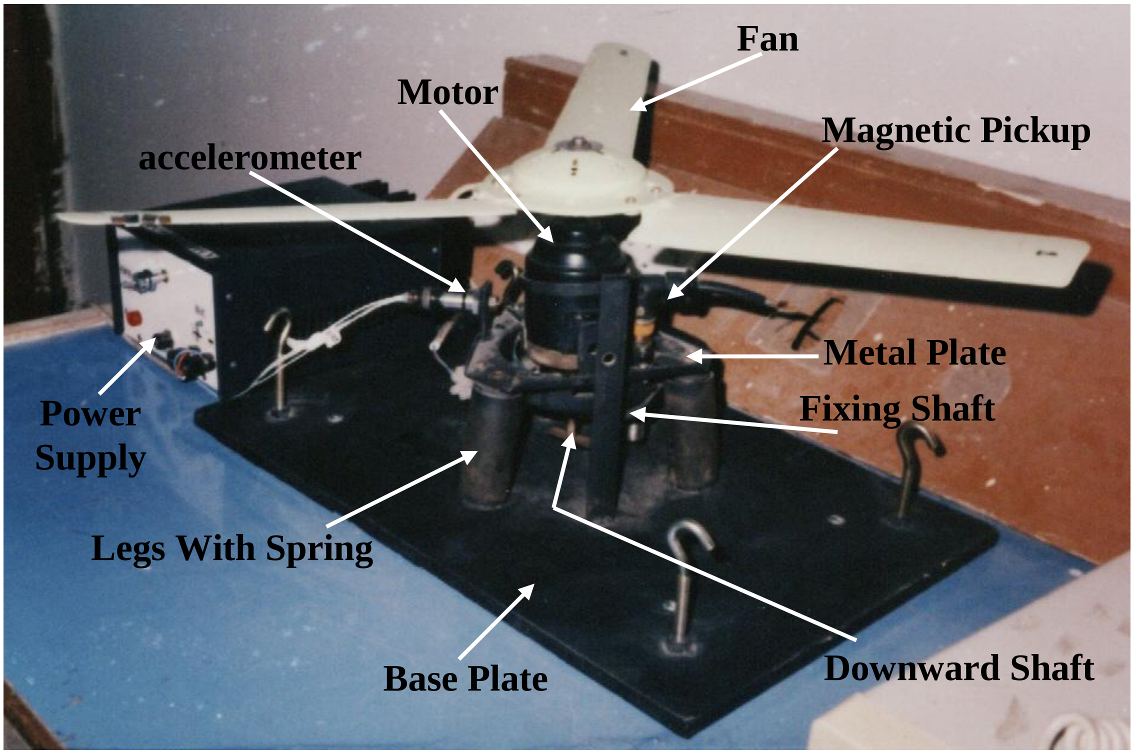


Fig. 12 The simulator.

PRACTICAL EXPERIMENTS BY USING THE SIMULATOR

The system is tested using the simulators. During the test carried on the simulator, different cases were considered such as:

Different weights on different blades.
Different positions of the sensors.
Longitudinal axis of the accelerometer.
Different number of targets.
Different speeds (RPM).

The configuration relating the blades with target is shown in Fig. 13 This configuration is used during all tests. The term “heaviest” means that a weight is added to the correspond blade. The output of the experiment is phase shift (degree or Clock angle) and amplitude (Volt) of vibration. The final part of the experiment is to calculate the additive weights for balancing that can be calculated from the charts as explained previously.

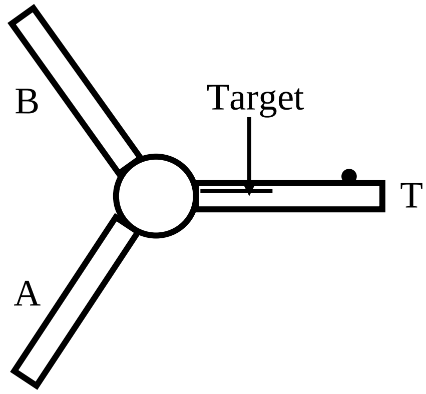
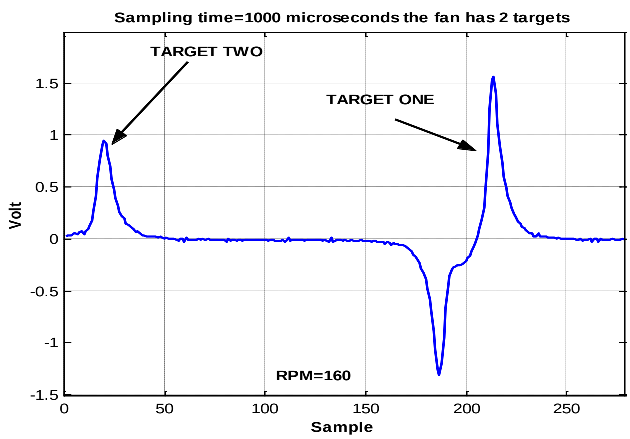


Fig. 13 The configuration relating the blades with target.



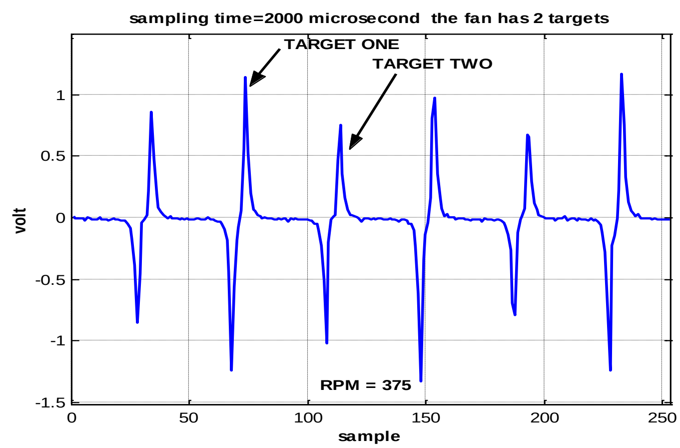


Fig. 14 Magnetic pickup output signal.

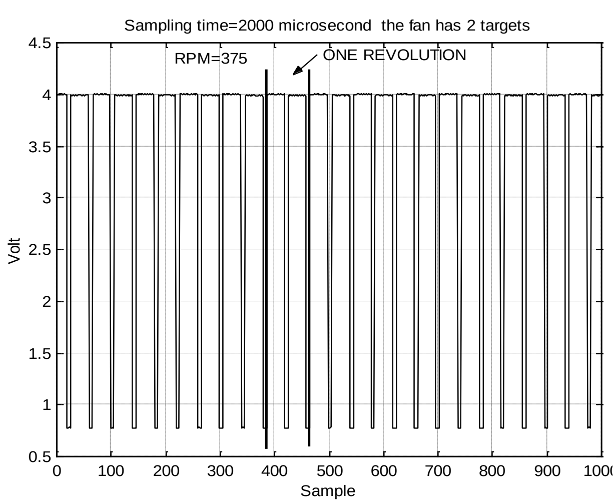


Fig. 15 Output of the second part (comparator) of the magnetic pickup signal conditioning.

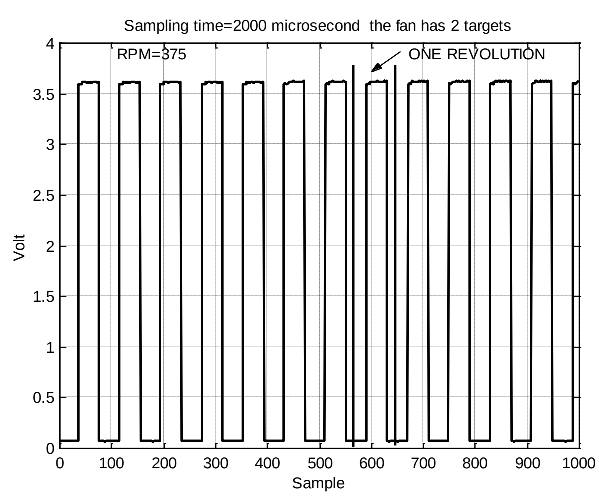


Fig. 16 Magnetic pickup signal conditioning output.

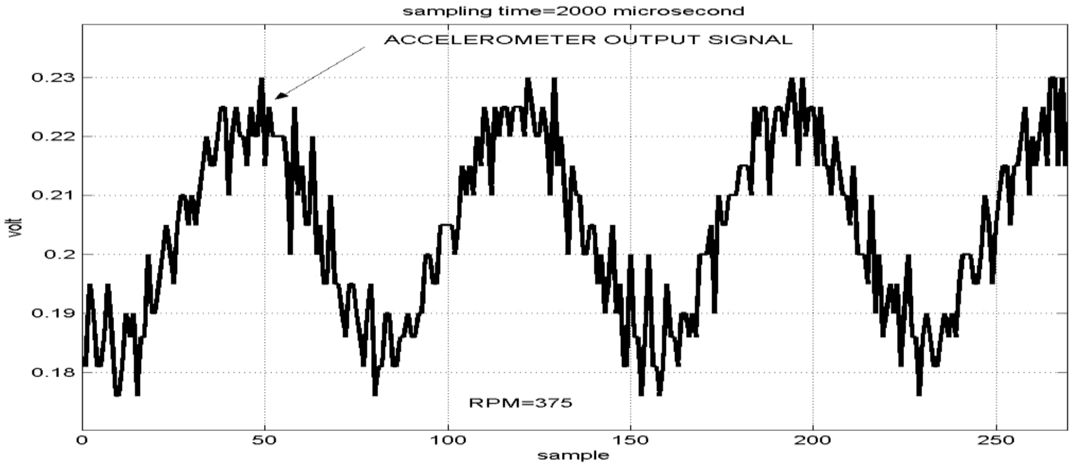


Fig. 17 Accelerometer output signal.

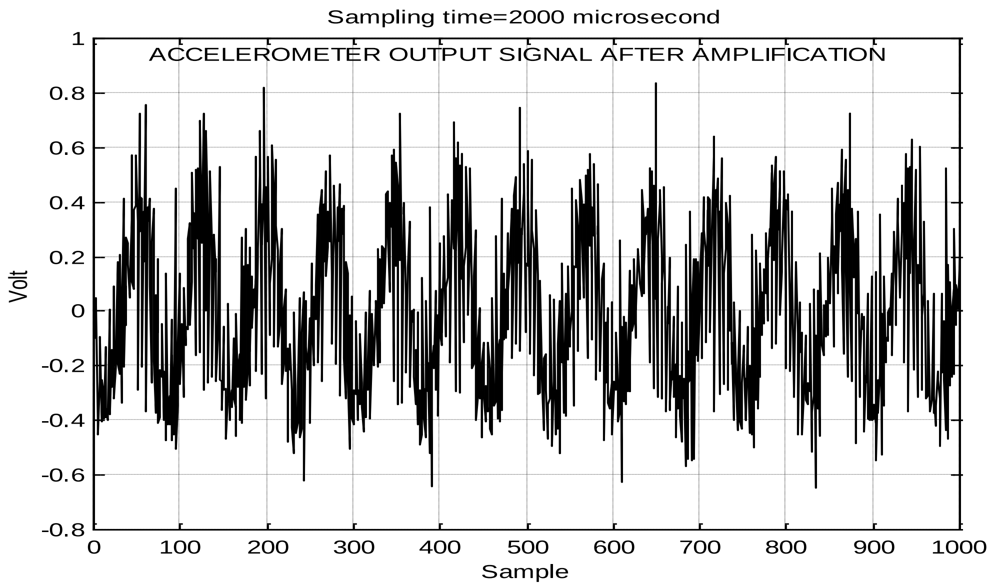


Fig. 18 Accelerometer signal conditioning circuit output.

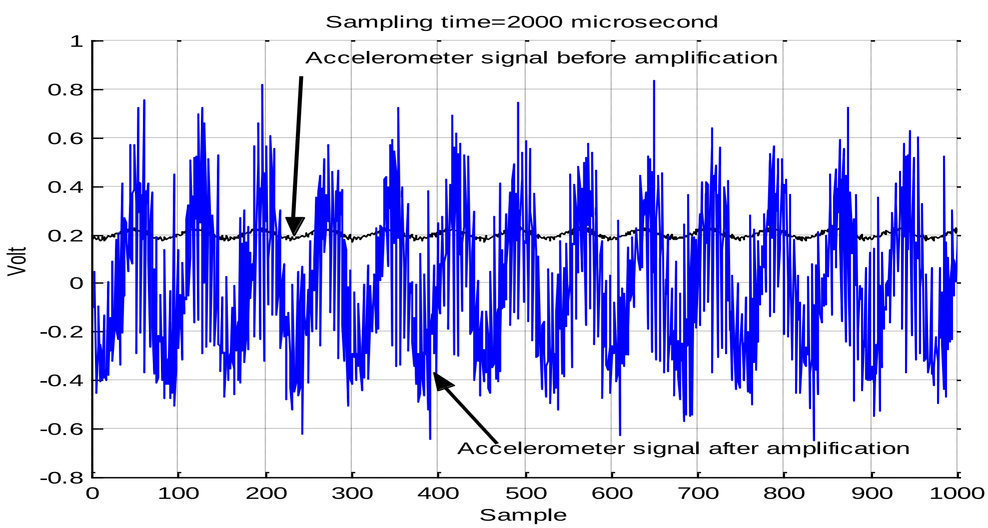


Fig. 19 Accelerometer signal before and after amplification.

Case (1):
The heaviest blade is T.
The fan has one target.
Angle between two sensors = 180 degr
Magnetic pickup frequency = 5.95 Hz.
Accelerometer frequency = 5.95 Hz.
Accelerometer average value = 0.6 vol
Accelerometer RMS value = 0.75 volt.
RPM = 357
Phase shift = 356 degree
Clock angle = 12
Case one is shown in Fig. 20

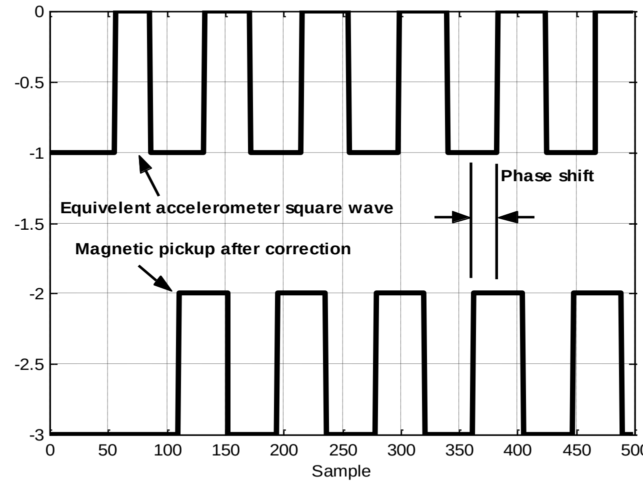


Fig. 20 Magnetic pickup and accelerometer waveform for case one.

Case (2):
The heaviest blade is B.
The fan has one target.
Angle between two sensors = 180 degr
Magnetic pickup frequency = 5.95 Hz.
Accelerometer frequency = 6.25 Hz.
Accelerometer average value = 0.55 vc
Accelerometer RMS value = 0.70 volt.
RPM = 360
Phase shift = 240 degree
Clock angle = 8
Case two is shown in Fig. 21

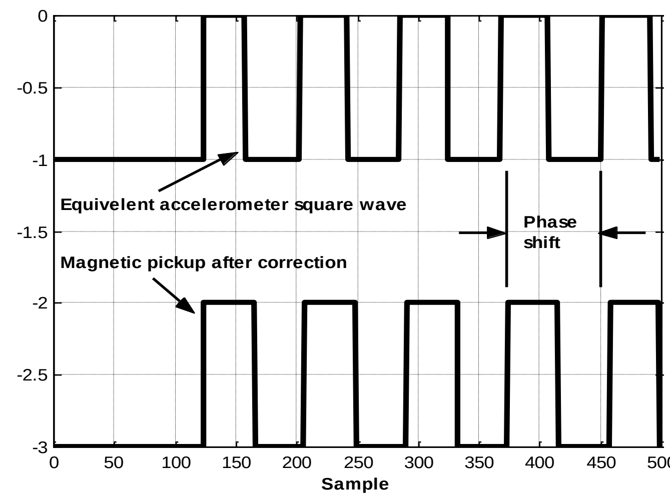


Fig. 21 Magnetic pickup and accelerometer waveform for case two.

Case (3):
The heaviest blade is A.
The fan has one target.
Angle between two sensors = 180 de
Magnetic pickup frequency = 5.95 H
Accelerometer frequency = 5.81 Hz
Accelerometer average value = 0.57
Accelerometer RMS value = 0.66 vo
RPM = 357
Phase shift = 110 degree
Clock angle = 4
Case three is shown in Fig. 22

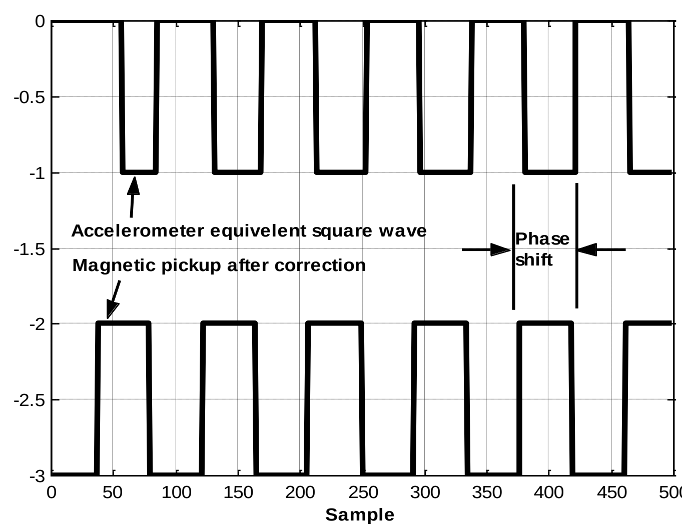


Fig. 22 Magnetic pickup and accelerometer waveform for case three.

CONCLUSION

- Vibration measurement and analysis is an important tool for creating a smooth operation of the machines The relationship between unbalance of a rotating body and the vibration produced is highly depended upon rotor speed and other operating conditions. When making vibration measurements for the purpose of determining and correcting unbalance, the operator must operate the machine in a consistent and repeatable manner to insure that repeatable measurements can be made.
- To measure the vibration due to rotor unbalance, a vibration transducer (sensor) is attached to the vibrating body when measuring imbalance. The vibration sensor converts this mechanical motion into an electrical signal that corresponds to the body's motion in space. The vibration analyzer is then used to sample this electrical signal and make various calculations based on the electrical signal's properties.
- In addition to the vibration measurement, a tachometer signal is collected. A tachometer sensor (magnetic pickup) is used to detect the position of the rotating body with respect to time. As in the case of the vibration transducer, the tachometer sensor converts this information into an electrical signal, which can then be sampled by the vibration analyzer and used in various calculations.
- The analyzer will collect a series of narrowband vibration readings called peak phase measurements since each reading is composed of a peak value and a phase reading. The peak reading (amplitude) is proportional to the amount of mass unbalance in the rotating machine.
- The phase reading (phase angle) provides information about the location of the mass unbalance. The analyzer based on the amplitude and phase angle of the vibration reading computes a balance solution (corrective weight) depending on charts that supplied by manufacturer. The corrective weight is then applied to the machine and the measurement process is repeated. The balancing job is finished when the vibration is reduced below an acceptable level (Prop and Rotor Balancing 2001).

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