Design and Implementation of Portable Vibration Analysis and Diagnosis System

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Abstract

In this work, a portable vibration analysis and diagnosis system is designed and constructed. The system is capable of doing most of the known analysis techniques such as FFT, time waveform, cepstrum analysis, dual channel analysis, orbit, envelope detection and other techniques. Furthermore, a new fast and efficient tracking analysis algorithm, suitable for portable instruments, has been proposed. This technique provides the data required to get accurate Bode and Nyquist plots for diagnostic analysis during machine run-up and coast-down tests. Moreover, FFT waterfall and spectrogram techniques have been included. Also, single-plane and dual-plane field balancing have been implemented in this system to execute field balancing tasks.

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الخلاصة : يتضمن هذا العمل تصميم وبناء نظام متنقل لقياس وتحليل الاهتزازات في المكائن الصناعية. يحتوي هذا النظام على اغلب تقنيات التحليل المعروفة مثل التحليل الطيفي ومخطط الاشارة الزمنية ومخطط طيف الطيف والتحليل ثنائي القناة وغيرها من التقنيات، هذا بالاضافة الى ادخال تقنيات جديدة مثل تحليل اهتزازت الحامل Envelop وتحليل الاهتزازت العابرة والتحليل المداري . لقد تم ابتكار تقنية جديدة للتحليل المرتبي او ما يعرف Tracking Analysis مناسبة للعمل على الاجهزة المحمولة تمتاز بالسرعة والدقة ويمكن استخدامها للحصول على البيانات المطلوبة لرسم مخططات بود ونايكوست لغرض تشخيص الاعطال اثناء بدء تشغيل او اطفاء المكائن. هذا بالاضافة الى وجود تقنية الشلال الطيفي والمخطط الطيفي الرسومي Spectrogram. كذلك تم اضافة امكانية اجراء موازنة موقعية احادية او ثنائية المستتوى حسب طريقة المعاملات المؤثرة.

Keywords: Vibration Analysis System, Dual Channel Analysis, Order Tracking Analysis, Field Balancing.

1. Introduction

Mechanical vibration is a very good indicator of a machine’s running condition and this is the reason why most common forms of condition monitoring use vibration measurements as an indicator [1]. Regular vibration monitoring and analysis programs are very useful in the industry. They allow the spare parts to be requested earlier, and determine the shutdown periods of a machine. They also predict the critical stops of a machine and prevent severe damages. As machines become smaller in size and more compact and complicated, vibration signatures become more complex to analyze and extract useful information about the causes of vibration. For example, multi-stage gear box and roller bearings produce high frequency harmonics which may be hard or impossible to detect unless using special techniques such as envelope and wavelet analyses [2, 3].

On the other hand, transient vibration analysis is very useful in detecting some system parameters such as resonance frequency and frequency response function. The technique is based on collection of vibration signal during the transient phenomenon and then analyzing it by FFT or other techniques. Machine run-up/coast-down tests are also special type of transient analysis in which machine speed is also collected to be a second parameter of analysis. Frequency response function or Bode plot can be obtained by plotting vibration amplitude as a function of machine speed and, hence, the resonance speed can easily be determined. Not only the overall vibration can be traced against the machine speed, but also speed orders (integer or fractional) can also be traced and plotted. The whole frequency range or FFT can be viewed against speed in the so called "Spectrogram" in which the vibration amplitude will be color coded. This is useful to readily detect which the order is the most likely the cause of high vibration [5, 6].

In dual channel analysis, vibration signals from two pickups are collected and analyzed simultaneously. Mostly, the pickups are positioned such that there is 90° phase-shift between them. This will allow tracing the exact movement of the shaft or the so called "orbit" [7]. Dual channel analysis is very important tool to detect some vibration problems which have similar FFT signature. A typical example is the case of unbalance and bent shaft since both of them produce 1xRPM vibration. However, unbalance will show elliptical orbit while bent shaft will show circular orbit. Many other faults will produce 1xRPM vibration, but the orbit will be non-elliptic or even banana shaped for misalignment problem for example. Both overall and filtered vibration can be used to plot the orbit. The speed and actual phase angle can also be measured to assist further in vibration diagnosis.

Field balancing is now widely applied for its features and benefits. The rotating parts can be balanced precisely in-place without the need to dismantle the machine. As a result time will be saved and actual running conditions will be met such as running speed, supports, coupling, electrical field and other effects. The method of influence coefficients is widely applied in field balancing due to its generality and accuracy [8]. To evaluate these coefficients, a number of trial runs must be executed with proper trial masses added during the procedure. Once these coefficients are calculated, they can be saved and recalled anytime to detect unbalance from a single run.

In this work, a complete system for vibration analysis and field balancing has been designed and constructed. The main part of the system is the portable device which was fully built in this work. It features two fully functional channel plus third channel for reference signal input. Vibration signals up to 50kHz can be analyzed and displayed as FFT with number of analysis lines up to 12800. Field balancing can be done at speeds ranging from 60 to 120000 RPM. The most important analysis technique is tracking analysis which was implemented by new fast algorithm.

2. The Implemented Portable Device

The portable device was fully designed and implemented in this work. The rapid developments and revolutionary advances in the production of electronic components, especially digital components, have led to built powerful portable devices with compact size and very low power consumption rate. These devices are ranging from multimedia, communication, medical, instrumentation, gaming and many other devices. Furthermore, the availability of multi-purpose efficient modules such as processor boards and DSPs has led to facilitate the building of powerful and dedicated devices such as instrumentation devices. Moreover, the application of some digital processing techniques eliminates or reduces the complexity and cost of the analog circuits. For example, digital filters are very powerful and flexible and successfully replace analog filters in many applications. However, some pre-processing on the signal is needed before converting it from analog into digital form. This includes low-pass anti-aliasing filtration and amplification to achieve good accuracy.

In this work, a portable device sized 20x12x5.5 cm and weight less than a kilogram was built. The device is shown in

Fig.1. Three main modules are built or acquired to construct the device, including analog module, ADC module and processing /display module.

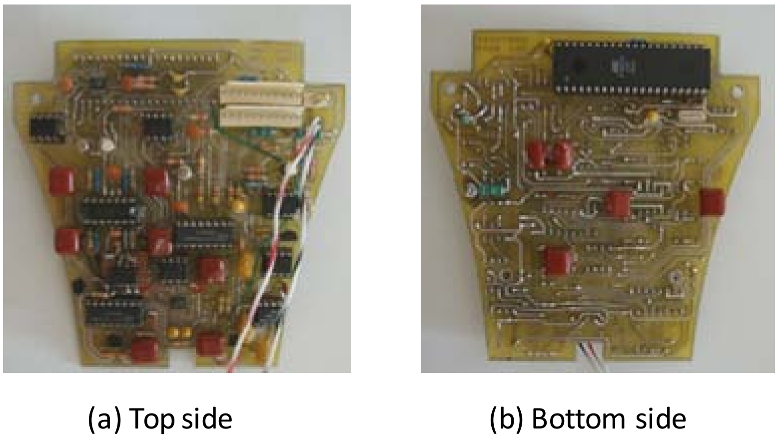
Figure 1 The Portable Device

2.1 Analog Module

This module was fully designed and constructed in this work. It is responsible for analog processing of signals including buffering, amplification in two stages, filtration and integration. Battery voltage and environmental temperature monitors are also included in this module. Some special integrated circuits are used to reduce the size and power consumption.

The printed circuit board was manufactured by utilizing the prototyping Printed Circuit Board (PCB) machine EP-2006. Fig. 2 shows the analog module while its block diagram is shown in Fig. 3. The buffer is useful to amplify small signals like piezoelectric accelerometer signal, while the DC-trimmer is used to eliminate any DC component in the input signal when only the AC content is required. The integrators are used to obtain velocity and displacement signals when the pickup is accelerometer. Analog implementation of the integrators is preferable due to their stability and to reduce processing and acquisition time. A dual-channel multiplexer is used to select between the integrated and direct signals. The first amplification stage is implemented using a dual-channel, high-speed and rail-rail amplifier to produce gain of 1, 2, 5, 10, 20, 50 and 100 for both channels. Each channel gain is separately programmable by the microcontroller. The proper gain setting is received from the processing unit through the ADC module. The anti-aliasing filter is achieved by utilizing a programmable 4-pole low-pass switched capacitor filter. The cutoff frequency is selected by the microcontroller by adjusting the clock frequency supplied to the filters. The second amplification stage is achieved by using similar circuit as in the first stage. The total amplification ranges from 1 to 10000 with 49 amplification stage which ensures high ADC accuracy and increases dynamic range. The device can efficiently implement autoranging to select the appropriate gain according to signal level.

A very low voltage-drop regulator fixed at 5v was built to regulate battery voltage and produce the positive rail, while a DC to DC converter is used to provide the negative rail voltage with sufficient current to operate the analog circuit and pickups. The unit is operated from 5.2v Ni-MN battery pack capable of providing more than 20 hour continuous running before recharged.


(a) Top side

(b) Bottom side

Figure 2 The Implemented Analog Module

2.2 Analog to Digital Converter (ADC) Module

This module is a general purpose data acquisition card from National Instruments (CF6004) features four 14-bit analog input channels and four digital input/output ports. The card interface is compatible with CompactFlash-II interface with maximum sampling rate of 200 kSample/sec for a single channel or 132 kSample/sec for multi-channel acquisition (aggregate sampling). Three of the bidirectional digital ports are connected to the microcontroller of the analog card to send commands and receive status. There is a certain command code to configure each programmable part in the analog module. Also, each command is followed by 1-byte or more data to configure the specified part. For example, to configure the first stage amplifier, a one-byte command code is sent to tell the microcontroller that it is required to configure the first stage amplifier, followed by 1-byte configuration data to select the gain. The fourth digital line is used to turn on and off the analog card to preserve battery voltage. Although this module has excellent performance, there is no software driver or library to be used by programming environment to communicate with it directly. The only possible option is to use Labview Mobile development environment to build a stand-alone executable that deals with this module. To solve this problem, a dynamic link library has been built to communicate with ADC module using native C language.

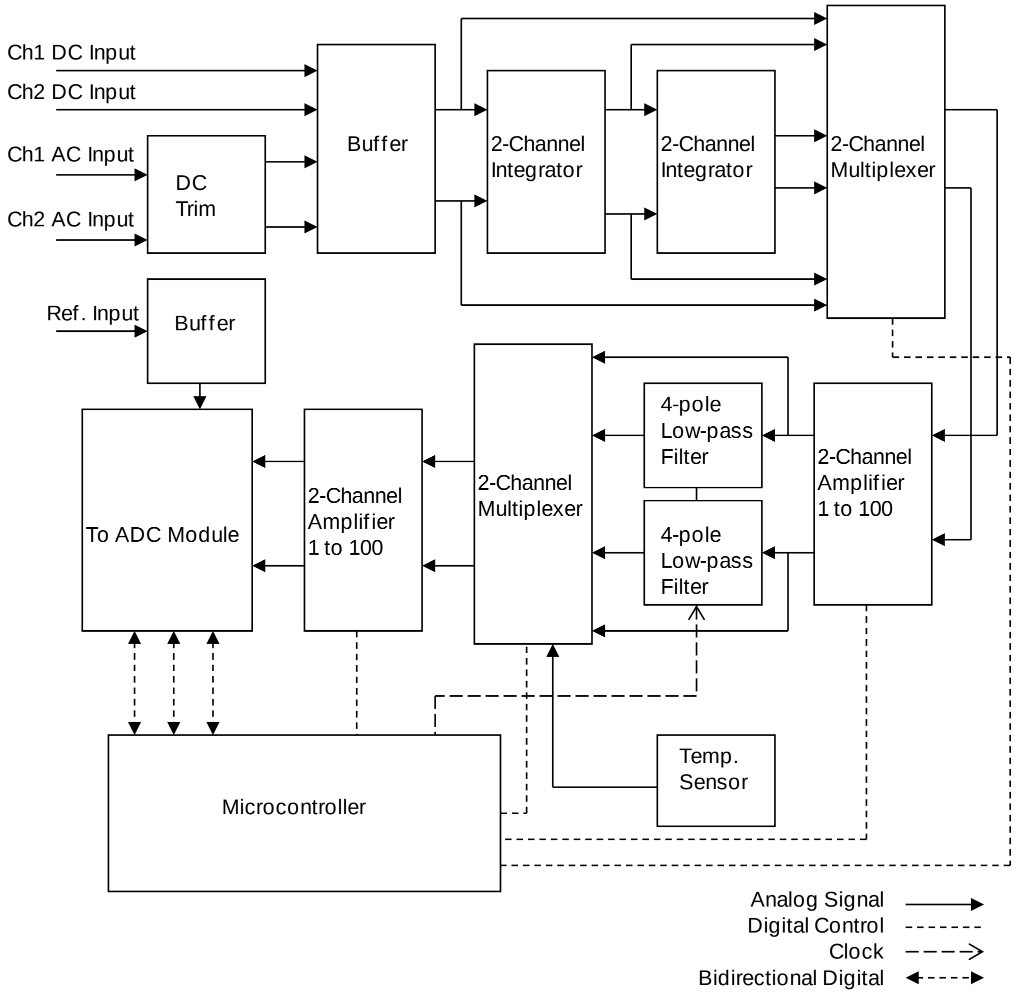


Figure 3 Block Diagram of the Implemented Analog Module

2.3 Processing and Display Module

This module is the heart of the mobile device. In fact, all digital signal processing tasks, calculations, data presentation, storage and many other tasks are held by this module. This module is a customized board that is used in the Personal Digital Assistant devices (PDA). It has OMAP3530 720MHz processor from Texas Instruments which has built-in Digital Signal Processor (DSP) TMS320C64 capable of performing 512-point complex FFT in few microseconds. It runs Windows CE 5.0 operating system and has 4-inch color touch screen. The high speed processor and large capacity have enabled the device to analyze signals up to 50kHz single channel or

25kHz dual channel with number of analysis lines up to 12800.

3. Common Analysis Features

Many vibration problems can be identified by using basic analysis techniques such as filtered level, time waveform, FFT and other techniques. The proposed handheld device can perform all the commonly used techniques in addition to some other useful single channel analysis techniques. Vibration level in terms of acceleration, velocity and displacement can be measured as overall or filtered within a predefined frequency range. This is useful to comply with some vibration severity standards or to measure vibration at a specific frequency range such as in high frequency detection.

FFT analysis can optionally be taken for a single point with maximum number of lines (bins) of 12800 and maximum frequency of 70 kHz. This is equivalent to a record length of 32768 points and sampling rate of 128 kHz. One of the most powerful enhancements regarding FFT analysis is that the device can perform Picket Fence Correction (PFC) to evaluate the exact frequency and amplitude through a sophisticated scheme [12]. Given that the frequency components are sufficiently separated, the PFC scheme can increase the frequency resolution more than 10 times.

Cepstrum analysis is useful technique to identify some problems such as harmonics in bearings and gears vibration [13]. The cepstrum is the inverse Fourier transform of the log power spectrum and it can identify harmonically related frequency components by a single Quefrency components whose delay (in seconds) is the reciprocal of the first harmonic.

On the other hand, envelope detection is widely applied in roller bearing and gearmesh fault analyses. It is a method for intensifying the repetitive components of a dynamic signal. The analysis includes filtration of the signal, squaring the signal and then applying FFT analysis. The low frequency vibration will be rejected during filtration process and only high frequency harmonics are passed. During harmonics-squaring, difference and sum components are created where the difference components fold back in the spectrum while most of the sum components are outside the analysis range [1]. The proposed device applies the following scheme to obtain envelope spectrum. The time signal is converted by FFT to frequency components [13];

$$A(f) = FFT\,[g(t)] \qquad (1)$$

Then, a frequency domain band-pass filter is applied by rejecting all components outside the desired range [14];

$$A_f(f) = \begin{cases} A(f) & f_l < f < f_h \\ 0 & otherwise \end{cases} \quad (2)$$

Where f_l and f_h are the lower and higher cutoff frequency respectively. The time window function ensures no or minimal power leakage from one to another analysis line. After filtration, the signal is converted back to time domain by inverse FFT, squared and then converted again to frequency domain to obtain the envelope spectrum [1];

$$Env(f) = FFT\left[\left(FFT^{-1}[A_f(f)]\right)^2\right] \quad (3)$$

The difference components of each harmonic series will be summed and displayed as single component at the first fundamental frequency.

4. Order Tracking

The run-up and coast-down tests are executed by analyzing vibration signals that vary with the speed or time as the machine speed goes up or down. One of the most common applications is detecting resonance related problems in rotors and structures [5, 6, 9]. Not only the resonance frequency can be detected, but also the order at which it occurs. One of the most important analysis features in the proposed device is its ability to extract the dominant orders or frequency components efficiently. Order tracking techniques are divided into two main categories, waveform reconstruction and non-reconstruction schemes [15]. In the first category, the specific order/frequency component is extracted and the time signal is reconstructed such as in Vold-Kalman (VKOT) and Gabor order tracking (GOT) [15, 16]. On the contrast, non-reconstruction schemes can process signals in the frequency domain or order domain to extract the amplitude and phase without reconstructing the time waveform such as the Time-Variant Discrete Fourier Transform (TVDFT) method [17] or Short-time Fourier transform (STFT). Both VKOT and improved GOT provide accurate information about the selected orders and can efficiently recognize and separate close orders or crossing orders [15, 16]. However, they require a lot of mathematical calculations which make them unsuitable for the portable devices or even tiny computers. On the other hand, TVDFT proposed by Dilworth and Blough [17] is fast and near real-time algorithm (based on powerful PC) but need some refinement to make it more suitable for the portable instruments. The TVDFT algorithm is based on extracting the order/frequency component from the original signal in similar fashion as the DFT do but the basis (kernel) functions are of variable frequency. The idea is excerpted from Fractional Fourier Transform (FRFT).

$$C_m = \frac{1}{N}\sum_{n=0}^{N-1} x_n \exp\left(i\,\phi_{m,n}\right) \qquad (4)$$
$$\phi_{m,n} = 2\pi \int_0^{n\Delta t} o_m S\,(t)dt$$

Where N is the number of points is the record to be analyzed, C_m is the complex component, ϕ_n is the total angle of rotation up to the $n\Delta t$ time, $S(t)$ is the instantaneous rotation speed in *Hz*, and o_m is the order to be extracted. All other orders will cancel out during summation process. However, if there are some close or crossing orders/frequencies, some inaccuracies will be presented as a result of smearing or leakage [17]. To eliminate or minimize smearing, the orthogonality compensation scheme is applied using linear equations formulation as given in eq. (5).

$$\begin{bmatrix} \hat{C}_1 \\ \hat{C}_2 \\ \hat{C}_3 \\ \vdots \\ \hat{C}_m \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & \cdots & a_{1m} \\ a_{21} & a_{22} & a_{23} & \cdots & \\ a_{31} & a_{32} & a_{33} & \cdots & \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ a_{m1} & a_{m2} & a_{m3} & \cdots & a_{mm} \end{bmatrix} \cdot \begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ \vdots \\ C_m \end{bmatrix} \qquad \ldots(5)$$

$$\hat{C}_m = \frac{1}{N}\sum_{n=0}^{N-1} x_n\, W_n \exp\left(i\,\phi_{m,n}\right) \qquad (6)$$

Where $\hat{C}_k$ are the calculated (correlated) components and C_k are the actual components. The elements of a_{ij} are the cross correlation terms resulting from correlation between orders i and j. According to [17], these terms can be calculated from the following equation:

$$a_{ij} = \frac{1}{N}\sum_{n=0}^{N-1} \exp\left(i\,\phi_{i,n}\right)\cdot W_n \left(\exp\left(i\,\phi_{j,n}\right)\right)^* \qquad \ldots(7)$$

Where W_n is the anti-leakage window function and the star (*) denotes conjugation. It should be noted that, according to eq. (7), the cross correlation matrix is Hermitian matrix ($a_{ij} = a_{ji}^*$) and the diagonal terms are the sum of terms of the window function. The actual components can be evaluated using Gauss elimination method. Evaluating elements a_{ij} require application of eq. (7) $(m^2–m)/2$ times and that's mean $N.(m^2–m)/2$ complex multiplications which require extensive processing time especially under the portable platforms. To overcome this problem, the following algorithm is proposed in this work and verified to be time saving in many cases. Eq. (7) can be re-written as:

$$\begin{aligned} a_{ij} &= \frac{1}{N}\sum_{n=0}^{N-1} \exp\left(i\,\phi_{i,n}\right)\exp\left(-i\,\phi_{j,n}\right)\cdot W_n \\ &= \frac{1}{N}\sum_{n=0}^{N-1} \exp\left(i\,\phi_{i,n} - i\,\phi_{j,n}\right)\cdot W_n \end{aligned} \qquad \ldots(8)$$

It is obvious from eq. (8) that if there are equally spaced orders to be extracted from the vibration signal, elements a_{ij} with the same orders differences will be identical. For example, suppose that there are four equally spaced orders 1X, 1.5X, 2X and 2.5X, the elements a_{ij} are diagonally identical, so we need to calculate only the first row of the orthogonality compensation matrix except the first element a_{11}. The reduction factor is $M/2$ where M is the number of equally-spaced orders. Although the orthogonality compensation algorithm is capable of separating close and cross orders, it requires enough record length to overcome leakage problem [17]. The record length is adaptively selected in the proposed scheme by increasing it when there is one or more cross orders are detected and decreasing it elsewhere to minimize processing time.

5. Transient Analysis

Transient analysis is similar in some way to run-up and coast-down analysis since both of them deal with a transient vibration. However, during machine run-up/coast-down test, the overall collection time is much longer and the speed signal is also acquired since it is a parameter of analysis. Transient analysis is very useful to identify resonance frequency or to estimate Frequency Response Function (FRF) of a structure [4, 9 and 13]. For example, during impact test, the structure or machine is bumped by a hammer and the correspond-ding vibration is measured and either analyzed online or stored and analyzed offline. More than one impact can be executed during data collection and averaging process can be performed over the overall record length with or without overlapping. In most cases, 50% overlapping is good choice to cover all signal details [13]. Logarithmic averaging is also applied where the log of the amplitude is used instead of the direct amplitude. Also, the peak amplitude is sometimes used instead of the averaged amplitude for better identification of the resonance frequencies, but this is applied when the noise is low.

The proposed device can collect transient analysis data for single or dual channel application. The collection process can be started manually or automatically depending on signal level but in the latter case, the maximum frequency will be limited to 10 kHz for single channel and 5 kHz for dual channel measurements compared to 50 kHz and 25 kHz respectively when using manual triggering.

6. Dual Channel Analysis

Dual channel analysis requires simultaneous sampling of two channels. The orbit plot is equivalent to the Lissajous pattern of two time signals connected to X and Y inputs of an oscilloscope [7, 9]. The implemented device provides the ability to sample the two channels in addition to the reference signal to obtain the exact orbital movement of a rotor. The overall or filtered vibration can be used to obtain it. When there is no reference input, the relative orbit is obtained considering one of the channels as the reference. The shape of the orbit will not affected, but it may be rotated by an angle from reading to reading. When a reference input is used, the actual phase angle between the two channels and the reference signal is known; therefore an exact and stable orbit is obtained. Another analysis technique includes dual FFT spectra, where the amplitudes, phase and frequencies can easily be compared between the two channels. Also, the time signals of the overall or filtered vibration can be displayed for the two channels.

7. Field Balancing

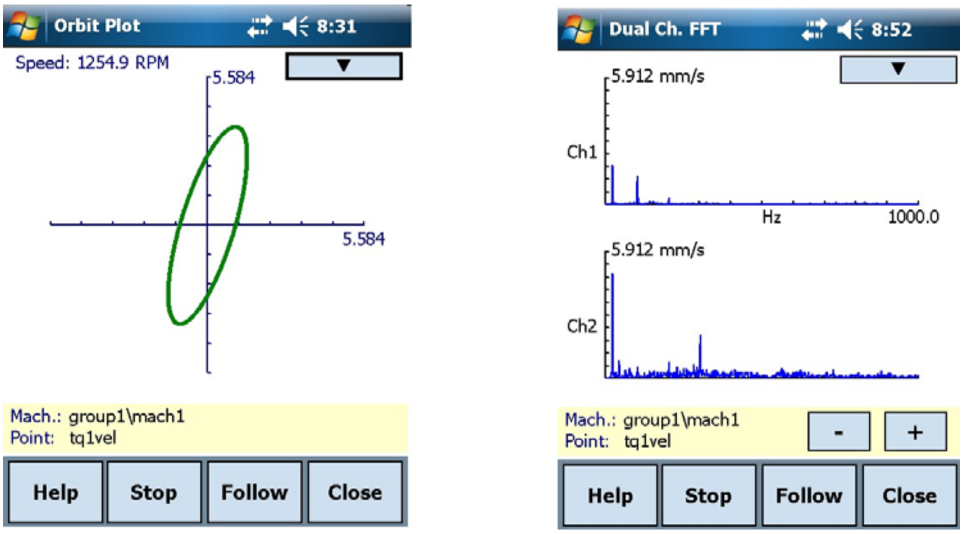
One of the most important features of a portable vibration analyzer is the field balancing capability. Some equipment have the provision to be in-place balanced such as fans, shafts, couplings, large turbo-machinery and others. Field balancing eliminates the need to dismantle the machine to perform workshop balancing. Also, field balancing can take into consideration the effects of the attached parts and thus producing good overall balancing condition. The proposed device incorporates one-plane and two-plane balancing scheme based on influence coefficients method [8]. To perform field balancing, a reflecting tape must be attached at some angle to produce reference mark to measure angles. Vibration signals must be collected during three runs, initial run, first trial, and second trial runs. The device will calculate the influence coefficients and calculate the initial unbalance. The influence coefficients are stored for future balancing procedures where a single run can be executed to estimate unbalance.

8. Experimental Results

8.1 Dual Channel Measurements

The measurements were taken on Tecquipment Whirling of Shafts apparatus shown in Fig. 4. Two pickups are attached to the motor-side bearing, in the horizontal and vertical directions. A photo-electric sensor is used to measure the speed of the motor and obtain a reference point. The motor was run at 1255 RPM which is slightly above the first critical. The resulting orbit for the filtered 1xRPM vibration is shown in Fig. 5a. The orbit shows a clear unbalance condition since it has elliptic shape [7]. In fact, the shaft has considerable unbalance due to bend condition. When the motor is run at 900 RPM, which is very close to the first critical speed, the shape of the orbit will be the same but the amplitude will rise to 11.5 mm/s as compared to 5.58 mm/s at 1255 RPM. Dual FFT plot in Fig. 5b clearly shows that 1xRPM vibration in the vertical direction (Ch1) is higher than horizontal direction (Ch2) which indicates looseness condition in the vertical direction.

Figure 4 Whirling of Shafts Apparatus



Speed: 1254.9 RPM
Mach.: group1\mach1
Point: tq1vel

Mach.: group1\mach1
Point: tq1vel

(a) Orbit for 1xRPM Filtered Vibration (b) Dual FFT Analyses

Figure 5 Motor-side Bearing Vibration

8.2 Order Tracking Test

To investigate the accuracy and efficiency of the proposed tracking analysis technique, a synthesis signal is generated by mixing three orders, 1X, 1.1X, 2X and a constant frequency signal of 50Hz. A run-up test is simulated with variable orders amplitudes as the speed increases. A constant angular acceleration of 7.5π rad/sec is assumed with speed ranges from 1200 to 4800 RPM (20 to 80 Hz). The Bode plot for uncompensated orders is shown in Fig. 6.

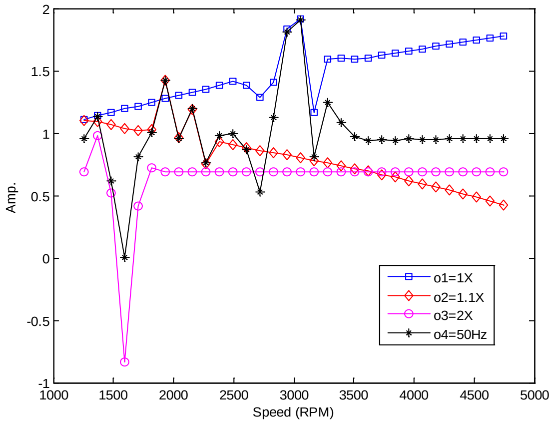
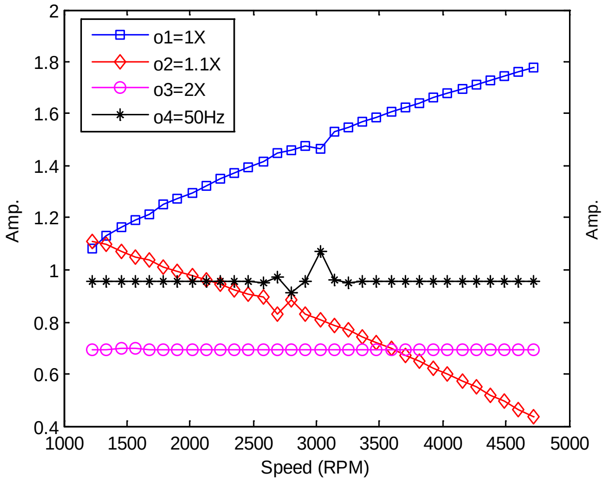


Figure 6 Uncompensated Orders

The uncompensated orders are highly correlated and distorted especially in the lower speed range and at crossing regions where orders cross the fixed frequency signal as shown in Fig. 6. This is due to the fact that at low rotation speed, the limited record length will results in more leakage from the actual components to the DC and nearby components. Also, it is clear that the 1X order is highly correlated to the fixed frequency signal (50Hz) when the speed is 3000RPM while the 2X order is correlated to it at speed of 1500Hz. After applying fixed-length of 256-point TVDFT algorithm, the extracted orders are now easily identified and well separated as shown in Fig. 7(a). However, there still some smearing at 1500 and 3000RPM in some orders. When adaptive-record-length algorithm is employed, the smearing is minimized as can be shown in Fig. 7(b).



(a) Fixed record length (b) Adaptive record length

Figure 7 Compensated Orders

8.3 Two-Plane Balancing

To verify the accuracy of the proposed device in two-plane balancing applications, the device was connected to B&K 3322 Balancing Machine shown in Fig. 8. The machine has two built-in accelerometers to measure vibration signals at the two flexible supports. A small rotor of about 3 kg in weight is used.


[redacted]

Figure 8 Dynamic Balancing Machine

The results are shown in Table-1 for the initial unbalance and residual unbalance after approximate corrections are made by adding the suggested masses. After the second correction, the residual unbalance is only 1/5 and 1/11 of the permissible unbalance in the left and right planes respectively. Another validation test is executed by attaching known weights to the rotor and then trying to detect them by the device. The results show excellent matching between the added and detected masses as shown in Table-2.

Table-1 Two-Plane Balancing Results

Rotor weight: 3 kg
Balancing speed: 1500 RPM
Permissible unbalance at left plane: 1.5 gm
Permissible unbalance at right plane: 2.0 gm

No.	Reading Type	Left Plane		Right Plane	
		Mass (gm)	Angle	Mass (gm)	Angle
1	Initial unbalance	1.41	95°	1.51	81°
2	After 1st trial	0.477	150°	0.152	295°
3	After 2nd trial	0.279	172°	0.171	280°
Ratio to Permissible		1/5		1/12	

Table-2 Validity Test Results

No.	Plane	Added Unbalance		Detected Unbalance	
		Mass (gm)	Angle	Mass (gm)	Angle
1	Left	3.00	340°	2.94	341°
2	Right	3.00	105°	3.02	104°
3	Left	3.00	270°	3.03	271°
4	Right	3.00	210°	2.95	211°

9. Conclusions

So far, a portable vibration analysis system has been designed and constructed. This system is capable of performing most of the commonly used analysis techniques in addition to some advanced techniques. One of the most important features is the ability of conducting in-field order tracking analysis for run-up and coast-down tests with provision of separating closely spaced orders and crossing frequencies/orders. The adaptive-record-length of the TVDFT algorithm is proved to very efficient in de-correlating orders contained in the vibration signal. The system is capable of conducting one-plane and two-plane field balancing. The conducted balancing tests have shown good accuracy since there is good matching between the created and detected unbalance.

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