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DEVELOPMENT OF AUTOMATED TEST MEASUREMENT SYSTEM FOR DETERMINING LOW PASS FILTER CUT-OFF FREQUENCY

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Abstract: Automated test and measurements systems provides autonomic computation of data that gives high accuracy, efficiency, resolution and precision in the measurement task. This paper presents the development of an automated test and measurement system to determine cut-off frequency of low pass filter. The software coding was carried out in the LabVIEW programming environment and appropriate hardware were setup to conduct test on series of low pass filter to validate the developed system. The test result shows high degree of accuracy which was validated via manual approach to confirm the effectiveness of the developed system.
Keywords: low pass filter, cut-off frequency, measurement, automation

INTRODUCTION

Filters are device that passes electrical signals at certain frequencies or frequency ranges and attenuate other frequencies. Filters are used in electronic circuit to remove unwanted components such as noise or interference from a processing signal [1]. They are broadly classified as linear or nonlinear, time variant or time invariant, analogue or digital, infinite pulse response or finite pulse response, and as passive or active filters [2]. In electrical electronics system applications, the design accuracy of filters to meet specific requirement is culminated by checking the filter frequency response via measurement test for the design validation. The accuracy in determining a filter cut-off frequency ensures that unwanted signal are perfectly removed from the processing signal of interest without attenuation. In sensitive application like communications that requires noise cancellations in modem, filters frequency response is vital due to closeness of noise and processing signal frequencies [3]. Considering the importance of filtering in signal processing for improved system performance, this work is focused on development of automated test measurement system for determining low pass filter (LPF) cut-off frequency that are commonly used in audio application to drive subwoofers.

The process of automation is regarded as a method of transferring engineering knowledge into machines that interprets commands and subsequently performs a task as programmed. Automated measurement systems are characterised with the ability to optimize their own behaviour on different platforms without human intervention to deliver high degree accuracy at shortest possible time [4, 5]. In this work, the basic structure of the automated measurement system consists of the controller and measurement instruments that communicates through GPIB, RS232, and RS432 channels. The developed automated test system for determining the cut-off frequency of a low pass filter has the advantages of high speed measurement, repetitive test ability, high accuracy, and the usage does not require special skill.

METHODS FOR DETERMINING CUT-OFF FREQUENCY

Low-pass filter (LPF) passes signals below the designed cut-off frequency and attenuate higher frequency signals. All the frequencies below the cut-off (f_c) point are unaltered with little or no attenuation [2, 6]. Low-pass filter exists in many forms like electronic circuits such has hiss filter for driving audio subwoofers and loudspeakers. They can also be digital algorithms for smoothing sets of data, acoustic barriers, blurring of images [7]. In low frequency applications up to 100 kHz, passive filters are usually built from simple RC (Resistor-Capacitor) networks while higher frequency filters above 100 kHz are based on RLC (Resistor-Inductor-Capacitor) components. Figure 1 shows a first order low pass RC-filter made of a single resistor and a capacitor in series across an input signal (V_{in}) with the output signal, (V_{out}) taken from the junction of the two components. As the input signal passes through the circuit, the high frequencies signal will be attenuated and only the signal below cut-off frequency of the filter determined by the RC time constant τ get to the output signal V_{out} .

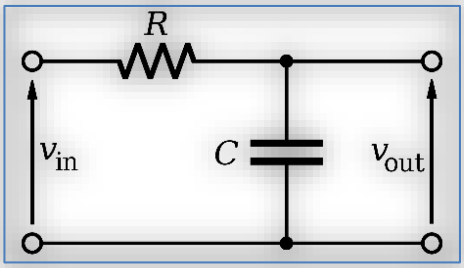

Figure 1. RC Low pass filter

The capacitor reactance of an ac circuit is given by:

$$X_c = \frac{1}{2\pi f}\Omega \quad (1)$$

And the impedance Z opposing the current flow from the input in the circuit (Figure 1):

$$Z = \sqrt{R^2 + X_c^{\ 2}} \quad (2)$$

The circuit voltage gain is defined by (3),

$$Gain = \left(\frac{V_{out}}{V_{in}}\right)^2 = \frac{1}{1 + R^2 4\pi^2 f^2 c^2} \quad (3)$$

The cut-off frequency of the low pass filter f_c is defined as the frequency point where the capacitive reactance and resistance are equal, $R = X_c$

$$f_c = \frac{1}{2\pi RC} \quad (4)$$

Therefore,

$$Gain = \left(\frac{V_{out}}{V_{in}}\right)^2 = \frac{1}{1 + 4\pi^2 f^2 c^2 . \frac{1}{4\pi^2 f_c^{\ 2} c^2}} \quad (5)$$

$$Gain = \frac{V_{out}}{V_{in}} = \frac{1}{\sqrt{2}} = 0.7071 \quad (6)$$

The popular methods used for determining the cut-off frequency of LPF includes graphical method, phase shift method, and the frequency scanning method. The graphical method involves plotting the gain in decibel (db) against the frequency. The frequency is varied from lower value to the higher value and as the frequency increases as the output voltage (V_{out}) decreases from the initial maximum value to lower value. The gain is calculated from the ratio of the input to output voltage which is plotted against the frequency and the cut-off frequency is defined as the point of 0.7071 which correspond to -3dB of the gain amplitude as shown in Figure 2 [7].

$$Gain(\text{db}) = 20 \log \frac{V_{out}}{V_{in}} \quad (7)$$

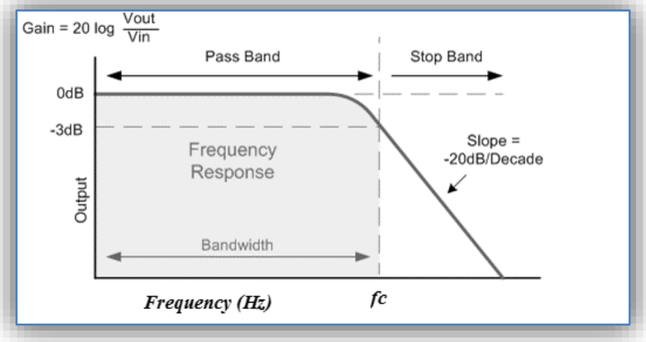

Figure 2. Frequency response of a LPF

The Phase shift method uses bode plot of phase angle against the frequency to determine LPF cut-off frequency. RC low pass filter has capacitor that charges and discharge making the phase angle (Φ) of the output signal V_{out} to lags behind the input voltage V_{in} due to the time taken to charge the plates of the capacitor as the input voltage changes. At -3dB gain amplitude which is the cut-off frequency (f_c) point, the output voltage is -45° out of phase as shown in Figure 3.

$$Phaseshift(\Phi) = -\arctan(2\pi \text{ fRC}) \quad (8)$$

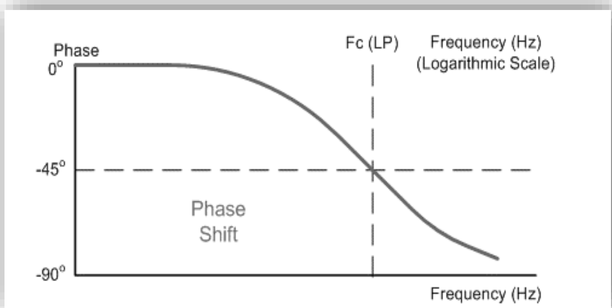

Figure 3. Bode plot of a LPF frequency response

The third method is the frequency scanning method. As the name implies, LPF cut-off frequency is determine by scanning filter frequency from higher to lower range. By scanning frequency to the input voltage at an interval, a technique for monitoring the gain is put in place to indicate when the ratio of the output to the input voltage is equal to 0.7071 which correspond to cut-off frequency (eqn. 6). This method is considered a fast method as compare to earlier discussed ones but it demands careful selection of measurement instruments. Also, the choice of frequency scanning rate must be well consider not to compromise the accuracy in the measurement. A highly sensitive comparator should be use to determining the point of equality between the gain from output to input voltage at the pre determine value of 0.7071. This method is mostly used in automated test and measurement systems owing to the advantages of fast, accurate and repeated measurement.

TEST AND MEASUREMENT TASK

The task of developing an automated test and measurement system to determine the cut-off frequency of a low pass filter involves an application of computer software program with the appropriate hardware set-up. The software part of the process was achieved using the LabVIEW graphical programming. Set of instructional code developed to communicate with the programmable instrument. The selected instrument for the measurement task are programmable and capable of receiving instructions from computer at fast speed.

Software development

LabVIEW programming software was used to developed set of instructional code to communicate with the programmable instruments. The software part of the measurement task automatically determine the cut-off frequency of low pass filter write the readings and saved on spreadsheet file for further analysis. The frequency scanning approach was adopted in developing the software programme and it covers the filter frequency range of between 50Hz – 10 KHz. This programme has four (4) loops as shown in Figure 4. The input frequency varies from one loop to the next loop where it is scale down to a range within which the cut-off frequency falls until it reaches the exact value. The programme start running from the first loop, as the frequency increases the gain from output to input voltage decreases until the condition of the comparator which is less than or equal to voltage gain of 0.7071 (voltage gain at cut-off frequency) is satisfy before the loop passes the process to the next loop. The measurement result is automatically display and saved in a file path. In the first loop frequency was scanned at the rate of 1000Hz and scaled down to 100 Hz in second loop. The third loop increment the frequency by 10 Hz each time the loop run and loop 4 finally scale it down to 1 Hz to achieve better resolution on the measurement.

The major elements in each loop are the GPIB read that reads byte count number from the GPIB device and GPIB write for writing data to the GPIB device identified by address string. There is a build text block used to create an output string from combination of inputs number entering it from iteration counter of the while loop and case structure. Prompt user interface displays as shown in Figure 5 is a dialog interface that prompts users to enter information about filter to be tested such as a user name or serial number. The write to measurement file save the measurement data to spreadsheet file for easy data management. The PXI controller house the software and provided the platform from where the system can be run to determine the cut-off frequency of the low pass filter and displayed on the screen.

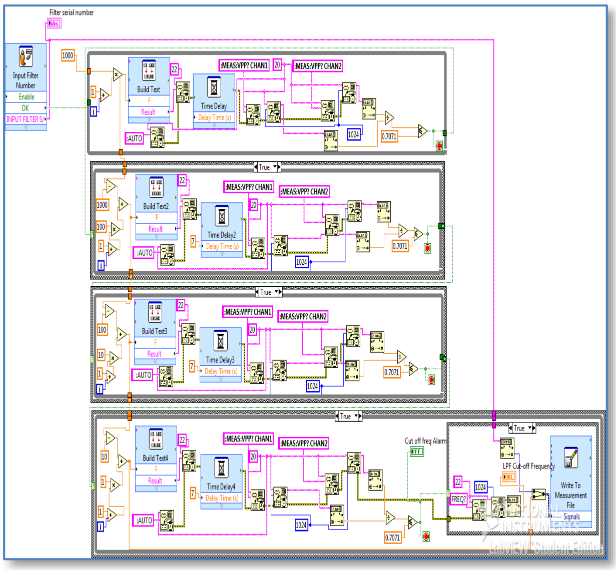

Figure 4. LabVIEW block diagram

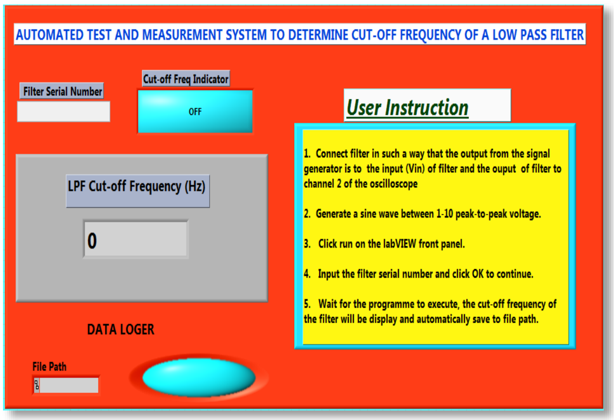

Figure 5. GUI Front Panel

Hardware Setup

The hardware set-up involves the use of programmable instruments that receive instructions from computer and provides the desire output signals with barest attenuation. The IEEE-488 General Purpose Interface Bus (GPIB) connector was used as communication channel between the instruments and NI-PXI computer with E-series data acquisition card to satisfy the high speed data transfer requirement in the automated system. NI-PXI PC-based platform is a Peripheral Component Interconnect (PCI) specially designed to offers a high-performance and low-cost deployment solution for measurement and automation systems [8].

The hardware components connection is shown in Figure 6, GPIB interface bus was used to connect the signal generator to the oscilloscope and also to the PXI. The output channel of the signal generator is connected to low pass filter (LPF) and the output peak-peak voltage from the filter is monitor on channel 2 of the oscilloscope. The application software programming on the PXI controller determines the cut-off frequency from the output voltage of the low pass filter read from the oscilloscope.

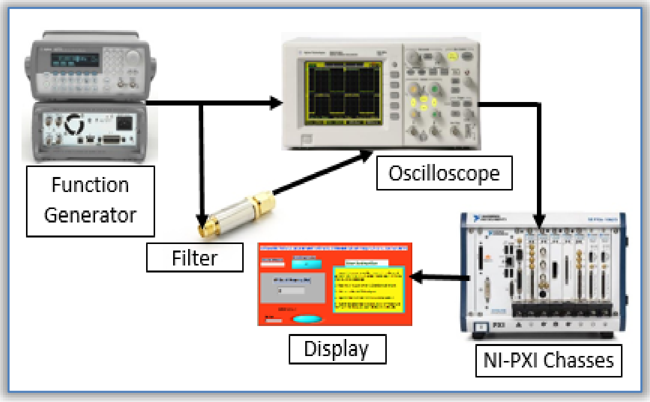

Figure 6. Hardware set-up for automation measurement

RESULT ANALYSIS AND DISCUSSION

An automation test and measurement system to determine the cut-off frequency of low pass filter was implemented using LabVIEW graphical programming language with appropriate hardware setup. The system was used to measure the cut-off frequency of low pas filter with serial number LPF23 and series of measurement was also carried out on 5 other different filters.

Automated Test on LPF23 Cut-off Frequency

The automated measurement system was used to automatically determine the cut-off frequency of low pass filter with serial number LPF23, a series of measurement was carried and the result were analysed to determine the performance of the measurement system. The measurement result is presented in Table 1, showing the cut-off frequency against response time for each measurement.

Table 1. Automated test cut-off frequency of LPF23

Cut-off Frequency (Hz)	Time Response (s)
1012	30
1012	30
1012	30
1013	32
1012	30
1015	33
1010	31
1011	30
1013	30
1012	30

Evaluation of Measurement Uncertainty

Measurement systems are susceptible to errors as a result of difference in measurement time and some external factors like environmental impact or changes in operational conditions. Considering the series of cut-off frequency measurement of LPF23 as shown in Table 2, there were little variation in the measured cut-off frequency.

Table 2. Automated test cut-off frequency of 5-LPF

Filter Name	1	2	3	4	5	Estimated cut-off frequency (Hz)
LPF 14 (Hz)	1594	1611	1603	1603	1607	1603
LPF 10 (Hz)	8201	8206	8225	8198	8101	8186
LPF 16 (Hz)	91	89	88	92	91	90
LPF 06 (Hz)	335	337	336	334	336	335
LPF 02 (Hz)	1371	1381	1374	1371	1370	1373

The difference can be averaged by uncertainty computation for random error in the measurement results to determine the true value of the cut-off frequency. The number of measurement (N) is ten and the best estimate of true value of cut-off frequency is calculated as follows:

$$\text{Mean } \bar{x} = \frac{\sum x_i}{N} = 1012.2\text{Hz}$$

The standard uncertainty S_N in the measured values of the cut-off frequency is:

$$S_N = \frac{\sigma_{N-1}}{\sqrt{N}},$$

where σ_{N-1} is population standard deviation

$$\sigma_{N-1} = \sqrt{\frac{\sum (x_i - \mu x)^2}{N-1}} \quad (9)$$

$$S_N = 0.4163$$

For the expanded uncertainty, by using 95% confidence with the degree of freedom 9, from the student t-table k has a value of 2.26. The limit of uncertainty in the measurement of the cut-off frequency is 0.4163 by 2.26 which is $\pm$ 0.9409 Hz. Therefore, the cut-off frequency of LPF23 low pass filter is 1012.2Hz$\pm$ 0.9409 Hz.

Analytical Approach to Determine LPF23 Cut-off Frequency

In order to validate the designed automated test and measurement system, an analytical method was then used to determine the cut-off frequency of LPF23 filter for comparison. The manual approach involves varying the frequency of the peak-peak input voltage to the filter and the corresponding output voltage are noted. The voltage gain in decibel (db) was computed from peak-peak output voltage and plotted against the frequency. The peak-peak input voltage V_{in} is 10.4V and Table 3 shows the peak-peak output voltage V_{p-p} against different frequency obtained during the test measurement on LPF23.

Table 3. Peak-peak output voltage V_{p-p} at different frequency

	Frequency (Hz)	V_{p-p} (V)	Gain: $Gain(\text{db}) = 20\log\frac{V_{out}}{V_{in}}$
1	50	10.4	-0.000835142
2	100	10.4	-0.000835142
3	150	10.4	-0.000835142
4	200	10.4	-0.000835142
5	250	10.201	-0.168646976
6	300	10.201	-0.168646976
7	350	10.01	-0.332820378
8	400	9.801	-0.516094144
9	450	9.601	-0.695172534
10	500	9.401	-0.878020874
11	550	9.201	-1.064801313
12	650	8.801	-1.4508615
13	700	8.601	-1.650523
14	750	8.401	-1.8548822
15	800	8.201	-2.0641657
16	850	8.001	-2.2786165
17	900	7.801	-2.4984964
18	950	7.601	-2.7240873
19	1000	7.401	-2.9556938
20	1050	7.201	-3.1936457
21	1100	7.001	-3.4383004
22	1150	6.801	-3.6900464

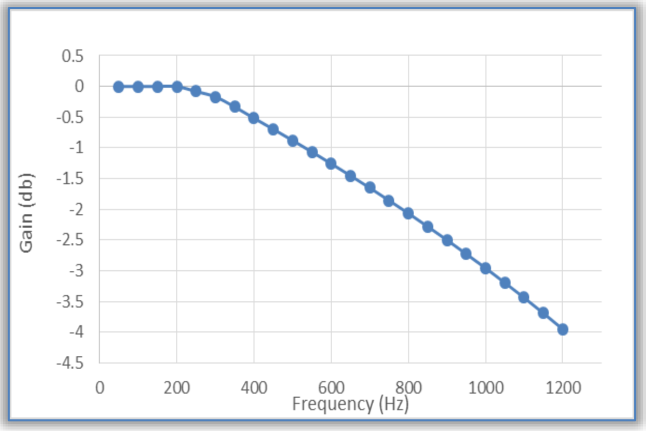

Figure 7. Gain (db) against frequency (Hz)

Due to rigorous of measurement with the manual approach, 22 different measurement was conducted at 50Hz range to reduce the measurement time. Figure 7 shows the plot of voltage gain (db) against frequency (Hz) and the cut-off frequency corresponds to $-3db$ point. In order to read the $-3db$ point accurately from the graph due to large frequency range, the point was interpolated for the corresponding frequency. The cut-off frequency is 1011.59Hz which is very close to averaged value of 1012.2Hz obtained from the automated measurement.

$$\frac{1050 - f_c}{3.1936 - 3.0103} = \frac{f_c - 1000}{3.0103 - 2.955}$$

$$f_c = 1011.59\text{Hz}$$

CONCLUSION

An automated measurement system was successfully developed using LabVIEW programming language as the standard commands for programmable instrument (SCPI) in passing commands to the programmable instruments during the measurement process. Series of measurement were carried out to determine cut-off frequency of low pass filter and the system was found to be accurate and fast for determining the LPF cut-off frequency. The automated test measurement was validated using the manual approach and the two results were almost the same. The automated measurement was achieved in a very short time as compared with the manual approach that was time consuming and it provides for repeated measurement.

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