

# Use of Software for Real-Time Spectrum Analysis\*

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*This paper describes a novel approach to laboratory teaching of Fourier analysis and related topics using readily available software running on an ordinary PC. In the past, the requisite spectrum analyser has been prohibitively expensive, but recent developments in audio acquisition cards and software mean that such experiments are no longer out of reach of all but the most well endowed departments. The experiments described are designed to familiarize students with the spectrum analyser and some measurements that can be made with it. Typical tests possible deal with its principles of operation and with its application to the visualization and measurement of frequency spectra and may be extended to encompass illustrations of frequency response.*

**Keywords:** electronics laboratory; fourier analysis; frequency spectra; spectrum analysis; visualization

## INTRODUCTION

THIS PAPER DESCRIBES teaching experiments that may be undertaken using readily available software for real-time spectral analysis. Although the use of software for spectrum analysis is clearly not new, the classroom possibilities (including the ease with which fundamental experiments, which have previously been impossible or extremely difficult in a teaching setting, may now be demonstrated) have not yet been widely appreciated by many teaching faculty.

In many fields it is common practice now to have students undertake ‘virtual experiments’ using a simulation package running on a computer. Although sometimes necessary for reasons of economy, such a use of computers does not convey the practical details involved in doing experiments using real equipment. In the present case, the software is used to emulate a real spectrum analyser, while students still use basic and relatively inexpensive equipment for generating real signals. The present experiments are therefore not ‘virtual experiments’ or simulations. Exactly the same experiments could be operated using the same laboratory equipment, plus a real spectrum analyser replacing the computer and software, if the cost were not generally prohibitive.

PC software currently available for undertaking real-time spectral analysis includes Spectrogram [1], MATLAB/Simulink [2] and LabVIEW [3]. Of these, MATLAB and LabVIEW are widely used in academia but their licences are not cheap. By contrast, Spectrogram is a readily available application package running under PC/Windows, currently costing less than US\$50 (and trial and

educational versions are available free); of course, commercially available spectrum analysers cost many thousands of dollars. Spectrogram takes input from a commercial PC sound card, with bandwidth up to 24 kHz. Pico Technology markets a range of oscilloscopes and spectrum analysers [4] based upon computer software; their low-cost units have a lower bandwidth than Spectrogram, but their higher bandwidth models are more expensive than Spectrogram. Other systems currently available include Scope2k4 [5], priced at under US\$20 for software, which includes a spectrum analyser program from version 1.6 onwards, though its bandwidth is limited to 4 kHz; the user must construct a suitable A/D interface, although these may also be purchased in small quantities.

Since many PCs are currently sold with a sound card (and sometimes a microphone) bundled with the basic package, the present application was trialed using Spectrogram software, though an equivalent package could also easily be used.

## OPERATION OF THE SPECTRUM ANALYSER PROGRAM

The sound card in a computer acts as a very fast digital voltmeter. It measures the voltage at a specified rate, typically up to 48 kS/s. Fast Fourier Transform (FFT) software calculates the Fourier transform of a signal sampled regularly in time at a certain number (which must be a power of 2) of instants. Since the signal Fourier components usually change with time, the FFT spectrum is generally calculated several times per second. Just a few years ago only the fastest computers or dedicated hardware systems were able to perform a Fourier transform in real-time, but now even a

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modest PC is fast enough to run a respectable FFT program and thus to emulate a spectrum analyser. The spectrum analyser can be considered equivalent to a band pass filter whose centre frequency can be swept rapidly over the frequency range of interest. There is a trade-off between the number of samples used by each FFT, the time the FFT takes and the amount of fine detail visible in the result.

The main display of the Spectrogram program (Line plot) plots frequency horizontally and the amplitude of each frequency component is plotted vertically. This is the most useful display for an electrical engineer. In the alternative type of display (Scroll, or sonogram display), frequency is plotted vertically and time is plotted horizontally.

## EXPERIMENTAL

The equipment required for this experiment is: a standard laboratory function generator capable of sine, square and triangle waveforms and internal or external AM and FM (sometimes called VCF, voltage controlled frequency). The Tektronix CFG280 provides external modulation and the Hewlett-Packard 33120A provides internal modulation capability. Both of these have been used successfully. A simple audio signal generator (another of the same type of function generators may probably be used, if available) is needed if the first generator provides external modulation capability only. Also required are a conventional oscilloscope and a standard PC that is running Windows. The PC must have a soundcard (e.g. SoundMAX Integrated Digital Audio) offering at least one audio input, such as line in or microphone in and, in addition, a small microphone should preferably be available for student use. Spectrogram [1] software (or an equivalent package) must be loaded. The software must be supplied by the laboratory, as in this application it must be used together with the laboratory equipment, and this will also ensure its correct configuration. Although some students may also wish to obtain their own personal copies, it is not a practical requirement for the present exercise. One function generator is connected directly both to the conventional oscilloscope and to the audio input of the soundcard and the Spectrogram software is run to provide a real-time display of the input spectrum, mimicking a spectrum analyser. At this stage, the function generator should be producing unmodulated signals.

### Basic operation

The function generator is first set to produce a sine wave output at frequency 15 kHz with amplitude typically 30 mV peak to peak (assuming the use of a microphone audio input, or a greater amplitude if a less-sensitive audio input is being used). The conventional oscilloscope is used throughout to verify the settings and to provide a

Table 1. Parameters for first-time use

Sample rate: 48 kHz	Freq scale: linear
Resolution: 16 bit	FFT size: 8192 points
Type: mono	Freq resolution: 5.9 Hz
Display type: line plot	Low band limit: 0 Hz*
Plot type: signal	High band limit: 24,000 Hz*
Scale: 60 dB*	Average count: 10
Palette: CB	Pitch detector: off
Time scale: 0 ms	Recording enable: off
Cursor offset: 0 Hz	

more familiar display when unexpected results occur.

The spectrum analyser program is run in full-screen display. The parameters in Table 1 are suggested for first-time use: The parameters marked \* are to be adjusted as necessary throughout the experiment (by clicking STOP—Function—Scan Input). When these parameters are set up, the system gain is set to 0 dB and GRID is turned on.

Firstly, the display is examined and compared with what is expected. Spectrogram generally gives a display of a single spectral line, but it has a non-zero width. The display may be recorded conveniently on a Windows-PC using CTRL + Print Screen and then pasting the buffer memory (holding the resulting image) into a graphics editor for filing (see Fig. 1). There may also be some other noise peaks. When interpreting low-level signals displayed by the spectrum analyser, particularly when a logarithmic vertical axis that emphasises low-level components is used, students must be warned to distinguish between the signals that are important and those that are unimportant imperfections. Students need to get accustomed to how a sine wave is displayed here. Throughout this experiment, for each significant signal input, students should sketch the important aspects of the actual display, pointing out any deviation from the expected result and recording separately the heights of all peaks that seem to be relevant. A gently rising baseline level at low frequency, or sharp peaks close to  $f = 0$ , can usually be disregarded; these are often caused by a DC offset or hum breakthrough on the input. Any unexpected features observable in the conventional oscilloscope traces should also be recorded. Also, students should continually consider whether the spectrum analyser is telling them something significant that would be difficult to discern from the conventional oscilloscope.

### Harmonic distortion

The generator frequency is then changed to 2000 Hz and the changes on the display noted and sketched (see Fig. 2), again commenting particularly on any unexpected features. The same is repeated at 150 Hz. Generally, distortion-related harmonics appear at this time (at 15 kHz, previously, the second harmonic is outside the range of the display). However, it is difficult to tell from the display alone whether these defects

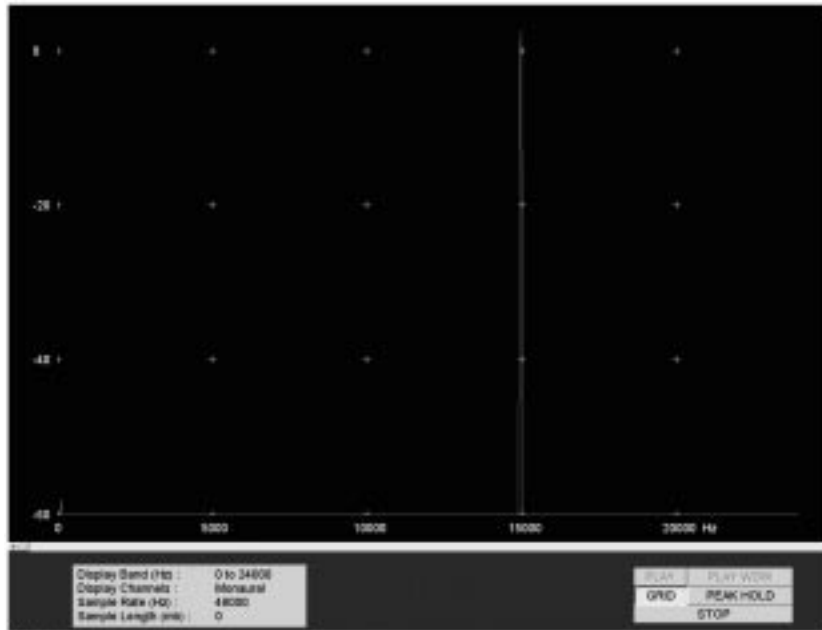


Fig. 1. Actual Spectrogram display of a 15 kHz sine wave with no distortion products visible.

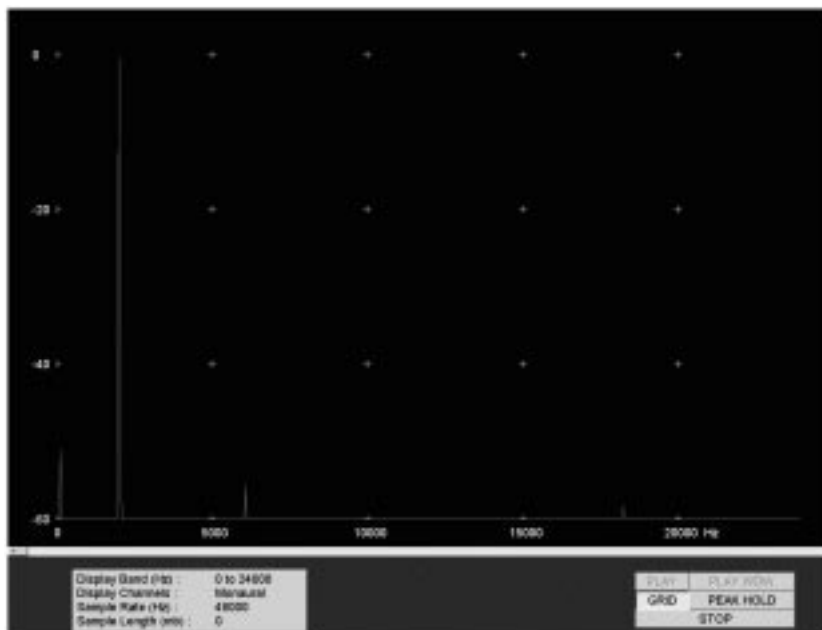


Fig. 2. Actual Spectrogram display of a 2 kHz sine wave, showing third harmonic distortion at around -55 dB.

arise in the signal generator or the sound card used. At this point, the definition of percentage harmonic distortion in a sine wave is defined and calculated from the display. This requires conversion from dB to voltage amplitudes. In a typical setup, the harmonic distortion is around 0.1% or about -60 dB. The point may be made that total harmonic distortion is not necessarily equal to the sum of the individual harmonic components. This is because the harmonic signals are sinusoids, so that adding them must take account of their phases, which are usually not displayed directly

by a spectrum analyser. To get the total harmonic distortion, usually another method is used such as a notch filter to reject the fundamental only, then measuring the amplitude of whatever is left. This is not easily done using a spectrum analyser.

#### *Square wave display*

The generator settings are changed to produce a 1 kHz square wave of amplitude typically 100 mV<sub>pk-pk</sub>, verified using the conventional oscilloscope. Again, the analyser display is recorded (see Fig. 3). From a square wave, the well-known

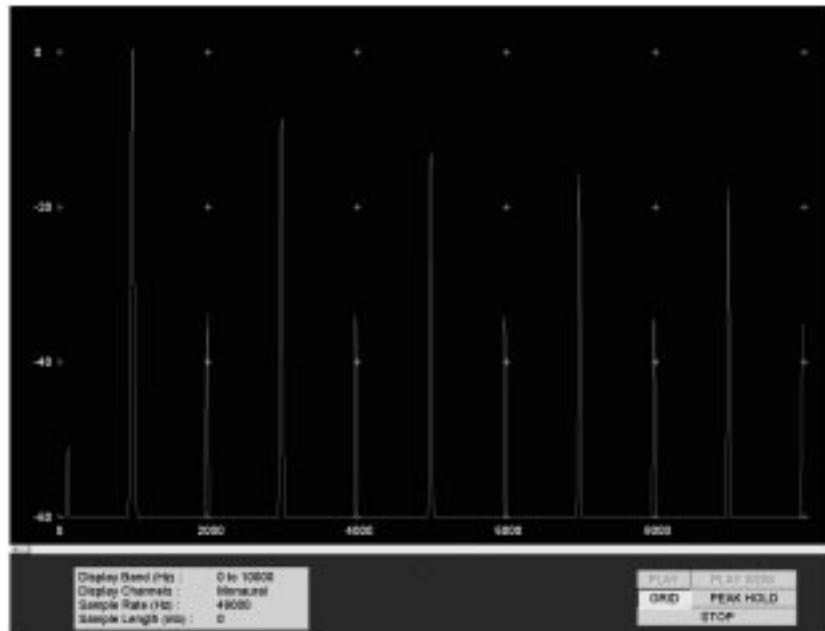


Fig. 3. Actual Spectrogram display of a 1 kHz square wave.

expected result is a series of odd harmonics reducing exactly in proportion to the harmonic number. In practice, some even harmonics are present as well (probably the generated square wave does not have exactly a 1:1 mark:space ratio) and the high odd harmonics do not decrease properly (probably due to defects associated with non-zero rise time).

#### *Sonogram display*

Changing the signal to a 1 kHz sine wave, the display type is changed to the Sonogram type (called 'Scroll' in Spectrogram). Frequency is now plotted vertically and time is the horizontal axis. The top line of the display is a real-time indication of amplitude, as in a conventional oscilloscope with a slow timebase (see Fig. 4). The generator frequency is slowly increased and the result observed. This type of display is widely used by researchers investigating acoustics, but electrical engineers usually prefer the spectrum analyser (Line plot) display because it gives a quantitative indication of signal levels. The rest of this experiment is conducted using the Line plot.

#### *Clipping*

The input signal level is slowly decreased, observing carefully both the conventional oscilloscope display and the spectrum analyser display. Decreasing the level should give results behaving as expected: the fundamental and harmonics should all move up and down as a block. Now increasing the signal above the previous level (nominally  $100 \text{ mV}_{\text{pk-pk}}$ ) causes the sound card to clip, so the display shows rapidly increasing levels of third harmonic and some second harmonic (see Fig. 5). The important observation is that these

harmonics increase more rapidly on a dB scale than does the fundamental peak.

#### *Other waveforms*

Reducing the level to the previous level (nominally  $100 \text{ mV}_{\text{pk-pk}}$ ) again and setting the generator to produce a triangular wave output and other waveforms available from the generator employed, allows the spectrum analyser trace to be compared with the known Fourier transform of each wave (see Fig. 6).

#### *Digital aliasing*

Setting the generator to produce a sine wave at 21 kHz at typically  $100 \text{ mV}_{\text{pk-pk}}$ , then 24 kHz, then 27 kHz (disregarding any small peaks) shows a simple illustration of aliasing caused by digital sampling (see Fig. 7).

Most sound cards include some filtering to reduce aliasing, but it is still visible on the display to some extent. To gain a clue about what is happening, students can set the frequency back to 20 kHz and slowly increase the signal frequency from there up to 37 kHz and even higher frequencies. Reduced sample rates can also be tried.

#### *Microphone and audio signals*

Resetting the sample rate to 48 kS/s and instead using a microphone to the spectrum analyser (if using a combined microphone/headset, the microphone plug is red), students can observe and record the traces produced by normal speech and by whistling at varying pitches. A toy whistle or another wind instrument, are useful sources of acoustic sine waves. A Swanee whistle can produce continually varying frequencies. The use of an harmonica, a descant recorder or a good singer

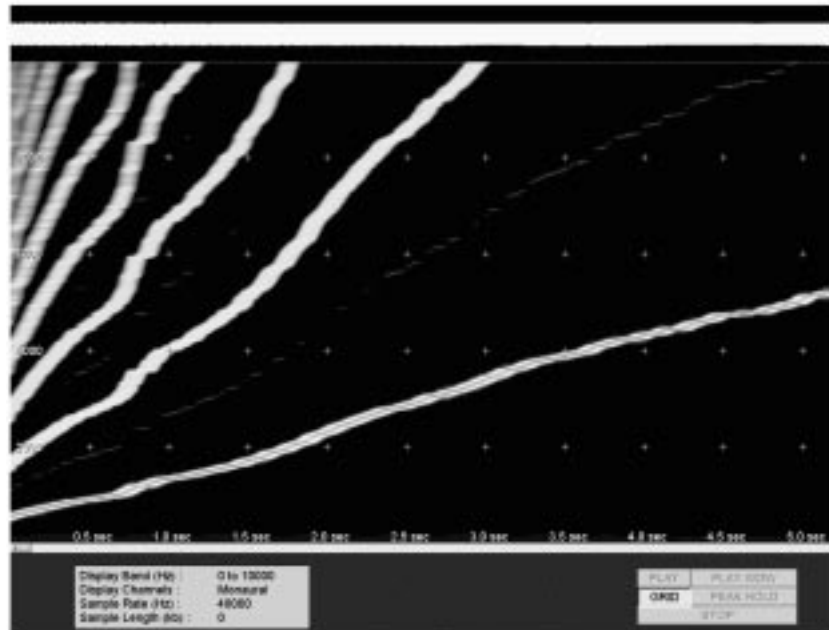


Fig. 4. Sonogram display of a square wave, steadily increasing frequency.

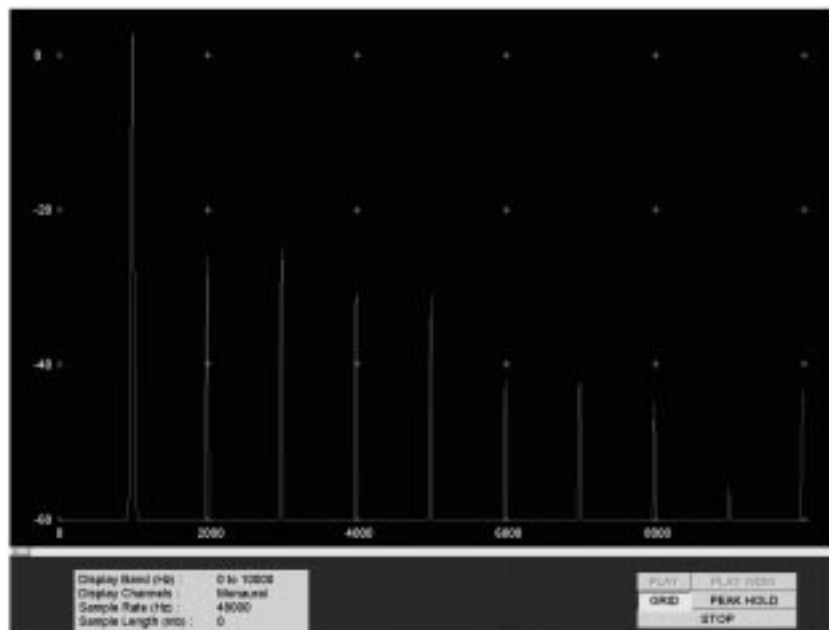


Fig. 5. Spectrogram display of a 1 kHz clipped sine wave (increased amplitude) showing prominent second, third and higher harmonics.

may also be tried. The differences between the conventional and Sonogram displays are interesting here.

#### *Amplitude modulation*

Setting the function generator to produce a 10 kHz sine wave of amplitude typically  $100 \text{ mV}_{\text{pk-pk}}$ , the second signal generator is used to feed a second sine wave to the first function generator's external AM input (or the internal AM source is used instead). (If using a sufficiently sophisticated function generator as the modulating signal generator,

it should be set to zero DC offset.) A modulation frequency of 1 kHz sine wave should be used first, at a typical amplitude of  $2.5 \text{ V}_{\text{pk-pk}}$  (suitable for many function generators used as the 10 kHz source including the Tektronix CFG280). The conventional oscilloscope should show both signals simultaneously by triggering it on the modulating (1 kHz) signal. Students should record the modulation depth (i.e. the ratio, to the maximum signal amplitude, of the difference between maximum and minimum signal amplitudes). The resulting display should clearly show

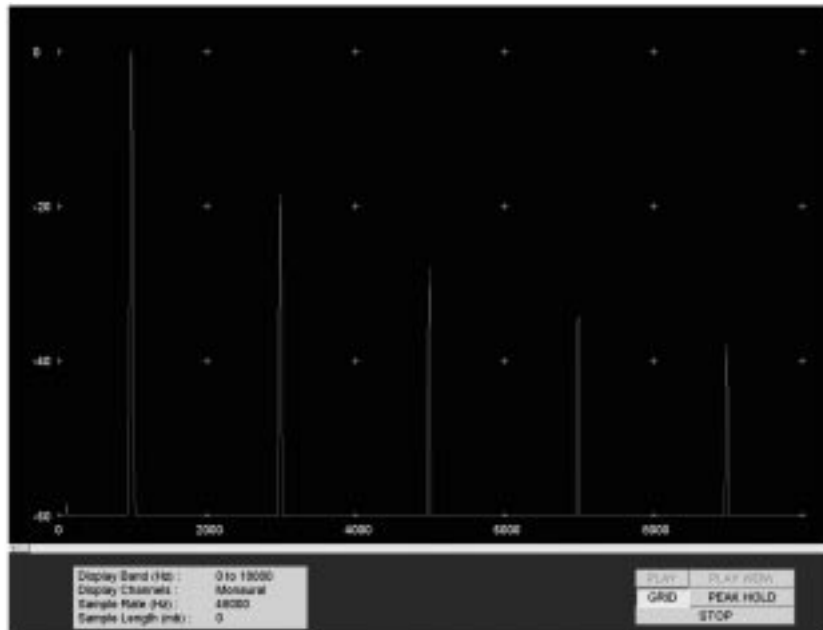


Fig. 6. Spectrogram display of a 1 kHz triangle wave, showing predominant odd harmonics decaying faster than for square wave.

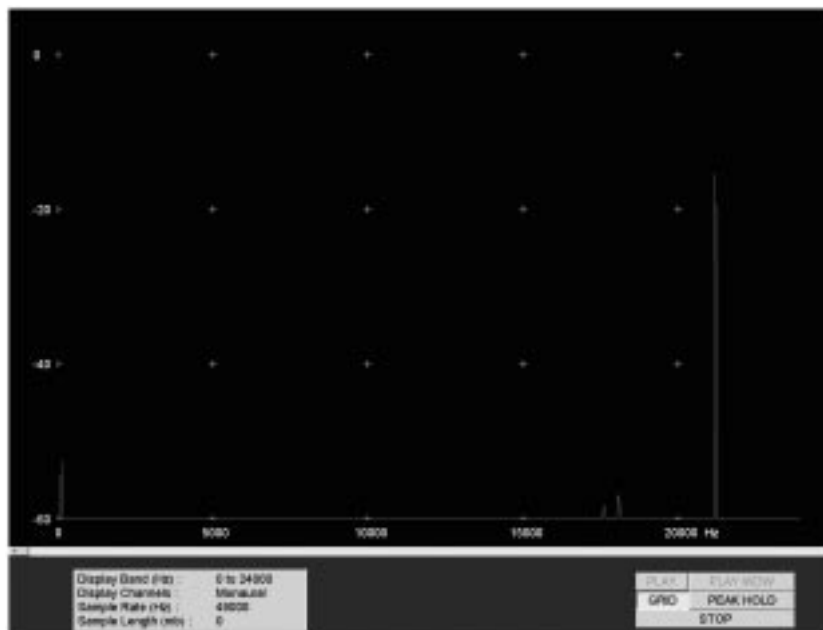


Fig. 7. Spectrogram display of a 26.5 kHz sine wave, showing aliasing (display at incorrect frequency).

the sidebands characteristic of AM (see Fig. 8). The issue of sidebands is often poorly understood by students and this may represent the first time they have seen direct experimental evidence of their existence. Students should experiment here by reducing the amplitude of the second sine wave and also adjusting the frequency of the second sine wave. However, they should not increase the second signal's amplitude significantly unless they can explain what happens when the function generator is overloaded! This produces a complex spectrum.

#### *Frequency modulation*

The second signal is next changed to the FM or VCF input of the function generator (or the internal FM capability is used instead). Again, students can estimate the modulation depth, which in this case is the difference between highest and lowest frequencies in the result, by triggering the oscilloscope from the first (i.e. the FM) signal. This displays a superimposition of the range of frequencies being produced and it is a simple matter to estimate from the oscilloscope time base the maximum and minimum frequency

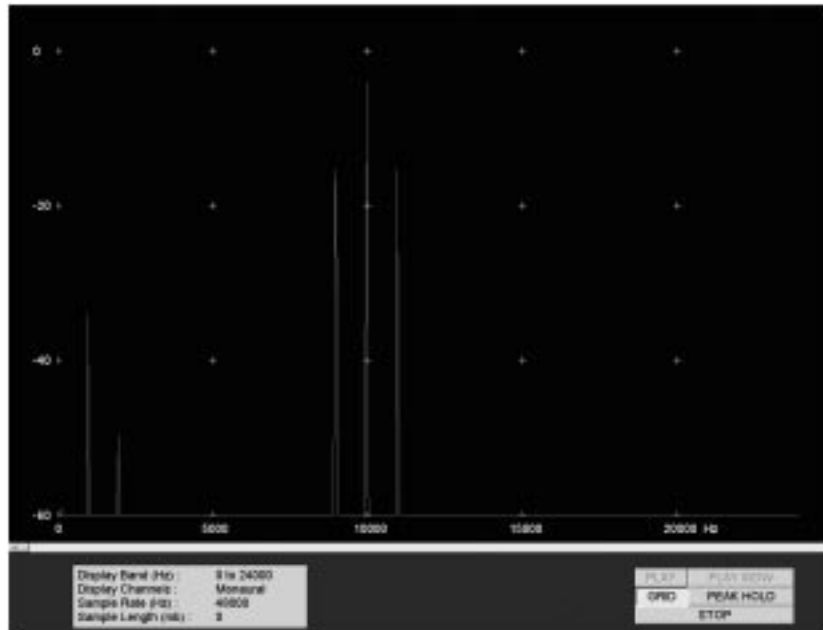


Fig. 8. Spectrogram display of a 10 kHz sine wave with 1 kHz AM, showing sidebands clearly.

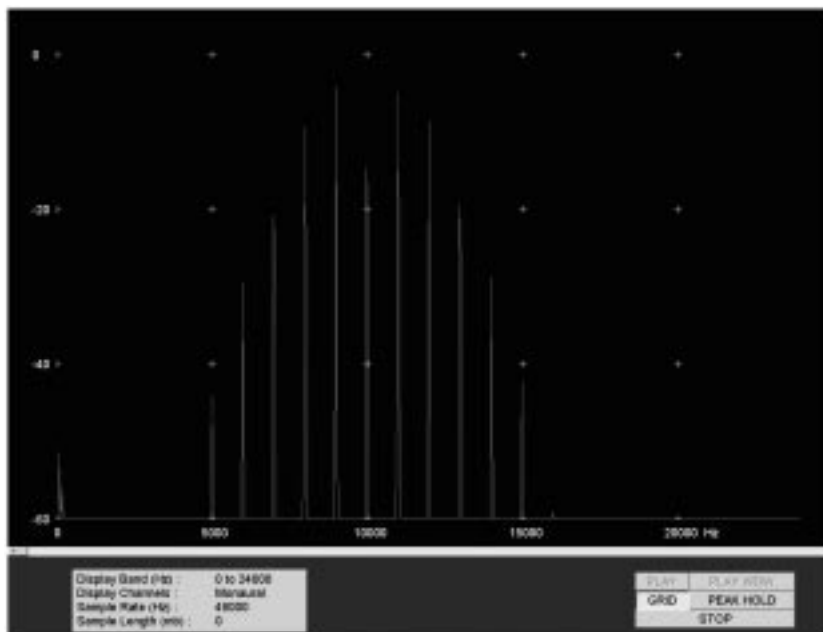


Fig. 9. Spectrogram display of a 10 kHz sine wave with 1 kHz FM, showing multiple sidebands clearly.

values. The spectrum analyser now displays the rather different (and perhaps slightly unexpected) pattern of sidebands in FM (see Fig. 9). The effects of adjusting the amplitude of the second sine wave (but, for simplicity, no more than the maximum allowed giving linear modulation) and also adjusting its frequency, may be recorded.

#### *FFT size*

Using any signal source, the effects of adjusting the FFT size may be observed. Generally, smaller sizes give poorer resolution, but are faster to calculate.

#### *Noise sources*

'White' noise is a signal that contains all frequency components equally over a specified range. Most basic analogue noise sources are 'white' because the origin of most electronic noise is the arrival at random intervals of single electrons, termed shot noise. Each electron arrival is equivalent to a  $\delta$ -function or instantaneous spike of current. Therefore, the Fourier transform of a  $\delta$ -function is a completely flat but non-zero spectrum.

A suitable white noise source circuit is shown in Fig. 10. This exploits the well-known white noise

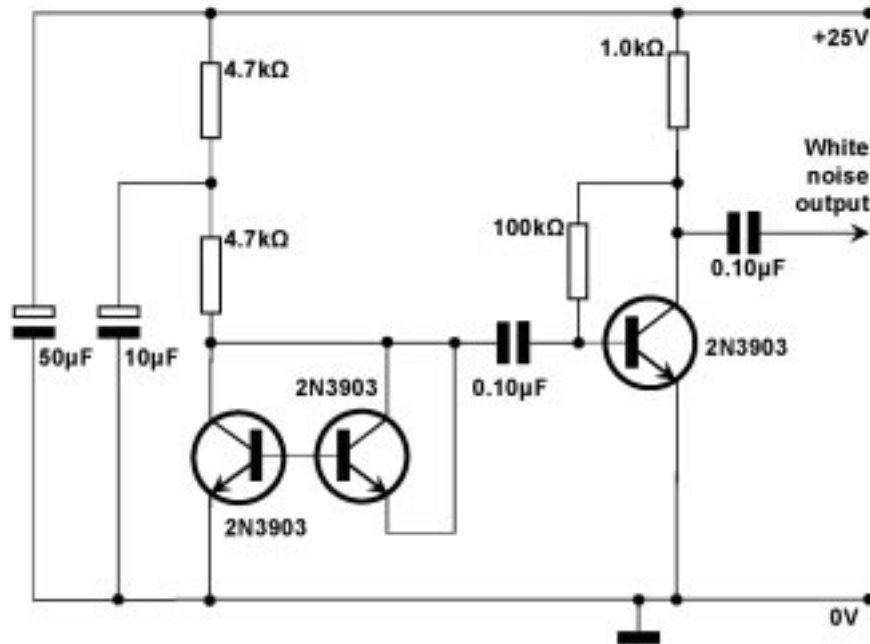


Fig. 10. White noise source. The supply voltage, transistor type and the values of the components are not critical. Almost any silicon planar npn transistors having  $V_{ce} >$  supply voltage could be used. A zener diode having breakdown voltage in the range 5V–15 V can be substituted for the avalanching transistor, though this usually gives smaller output amplitude.

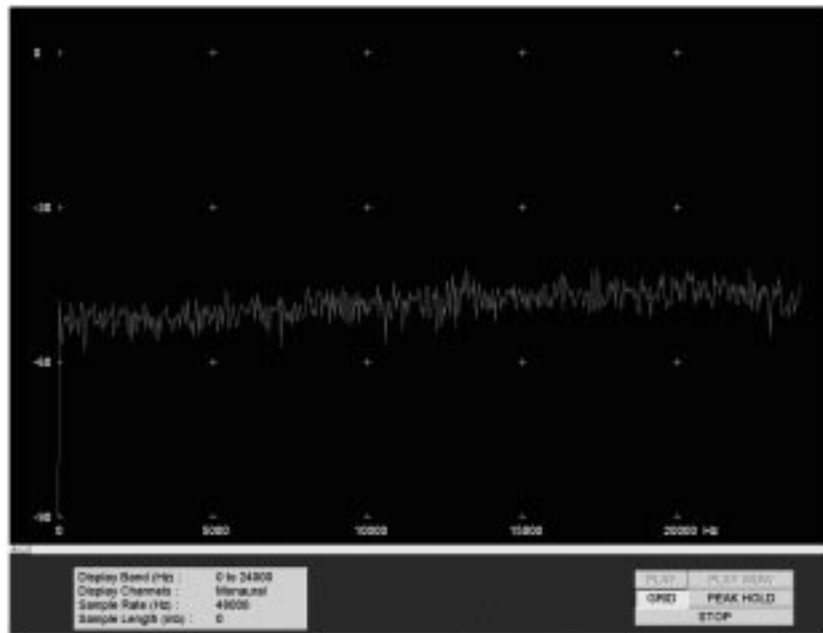


Fig. 11. Spectrogram display of output from a white noise source shown in Fig. 10.

characteristics of the shot noise created by avalanching in a reverse-biased diode (in this case the emitter-base junction of a silicon planar transistor, which usually breaks down at around 7 V). The function generator is disconnected and this white noise source connected to the microphone input of the PC (see Fig. 11). Enterprising students may try shaping this noise spectrum by connecting some simple filters (low-pass, high-pass, resonant) between the white noise source and the spectrum analyser and oscilloscope, though careful note

needs to be taken of the driving and driven impedances in this case.

#### Comments

Previously, Fourier transforms and the FFT were mostly taught as abstract mathematical concepts with little direct application that could be easily demonstrated. For example, prior to cheap FFT software being available, about the only inexpensive way to demonstrate sidebands was to use a variac to vary the amplitude of the



electrical supply connected to a resonant-reed frequency meter. This was limited to a carrier frequency of 50 or 60 Hz and modulation frequencies of around 1 or 2 Hz. Astute students were able to relate Fourier transforms to the frequency responses of sound reproduction equipment and its response to square wave excitation, but the complex sideband structure of FM signals has historically been difficult to demonstrate. This has resulted in FM being misunderstood by many students (e.g. in designing FM receivers with insufficient bandwidth). Clearly the advent of flexible DSP software has changed this and has enabled a vivid classroom experience demonstrat-

ing the fundamental points of Fourier transforms and spectral analysis.

## CONCLUSIONS

A useful and inexpensive way of teaching the practical consequences of Fourier analysis is to use inexpensive spectrum analyser software on an ordinary computer. The practical tests described here familiarize students with the spectrum analyser and some of the measurements that can be made with it.

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Professor Woods is an invited member of the international awarding committee for Marie Curie Fellowships supported by the European Commission in Brussels and of research funding panels at NSF, Washington DC. He has current research interests in novel solid-state devices, device modelling and magnetic recording and has authored more than 80 research publications in these fields. He is a Senior Member of IEEE and a Fellow of IET and ASEE.