Key-clicks and CW Waveform shaping

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1. Introduction

CW transmitted with poor waveform shaping causes interference that is heard as clicks and thumps by other CW operators on nearby frequencies. When I was first licensed in the early 1960's, there were few commercial amateur transmitters available and so most amateurs either constructed their own or used modified WW2 equipment. At that time transmitters used valves and often the Morse key was in the cathode circuit of the PA, as it was with my first transmitter, which was turned on and off with little or no attempt at shaping the keying waveform.

That was over 50 years ago and most amateurs now use commercially made equipment with capabilities that we could not have imagined all those years ago. So surely modern transceivers must generate CW RF waveforms that minimise the bandwidth occupied by the signal, as is required by the licensing regulations? It seems that many do not. Examination of the CW end of the HF bands using an SDR receiver will soon show CW signals with excessive sidebands, such as the example below.

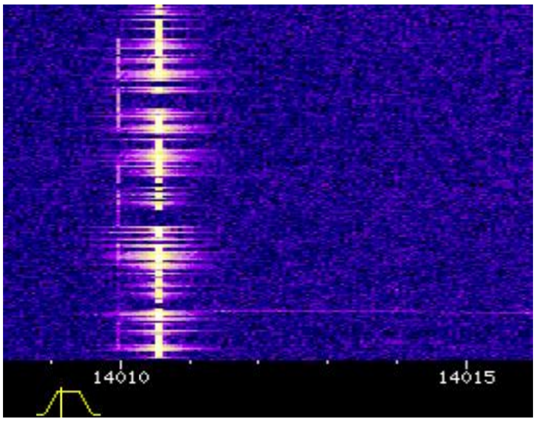


Fig. 1. CW transmitter with excessive sidebands

This article sets out to examine the shaping of CW RF waveforms in order to determine the rise and fall time profiles that minimise the bandwidth of the transmitted signal.

2. Bandwidth and sidebands

As radio amateurs, we are required to minimise the bandwidth of the signal that we transmit. Note (a) of the UK Licence states that:

> (a) The bandwidths of emissions should be such as to ensure the most efficient utilisation of the spectrum. In general this requires that bandwidths be kept at the lowest values which technology and the nature of the service permit. Where bandwidth-expansion techniques are used, the minimum spectral power density consistent with efficient spectrum utilisation should be employed.

It is well known that an amplitude modulated signal occupies a bandwidth twice that of the audio signal that is modulating the transmitter. Similarly, a CW signal occupies twice the bandwidth of the keying waveform.

For CW signals we must concern ourselves with two aspects, readability (by a human operator) and the bandwidth occupied. In reality, these tend to be mutually exclusive. CW signals with long rise and fall times occupy a small bandwidth but sound "soft" and may be difficult to read, whereas signals with short rise and fall times are easier to read under challenging conditions but occupy a greater bandwidth. A compromise must be made. The ARRL recognises this and suggests that CW signals on a fading communications circuit required faster rise and fall times, and consequently a greater transmitted bandwidth, than a non-fading circuit (Ref. 1).

There is also the question about the definition of "bandwidth" of a CW transmission. An attenuation limit needs to be specified but neither the ARRL, nor the RSGB in their UK band plan (Ref. 2), have defined a limit. The RSGB 2016 band plan states:

> NOTES TO THE BAND PLAN
>
> **ITU-R Recommendation SM.328 (extract)**
>
> **Necessary bandwidth:** For a given class of emission, the width of the frequency band which is just sufficient to ensure the transmission of information at the rate and with the quality required under specified conditions.

For the purposes of this article I will set an attenuation level for CW bandwidth, which I derive as follows:

Consider a strong CW station which is registering S9 +30dB – by no means unusual. We want to work another station close to it that is registering S4 – not a particularly weak signal. Assuming 6dB per S-point, then the wanted station is 60dB below the adjacent strong CW station. So I have adopted an attenuation of -60dB as the bandwidth limit. Key-clicks would still be audible but should not distract too much from the readability of the wanted signal.

There are two ways in which we could assess the effectiveness of the shape of the rise and fall times of a particular waveform. We can look at the amplitude of the sidebands of the worst case CW sequence, which is a continuous string of dots, in other words in the frequency domain. Alternatively we could look at the time domain, for example the effect of a keyed CW signal on a receiver tuned to an adjacent frequency. We will look at the frequency domain first.

A very long string of dots will produce discrete sidebands at multiples of the keying speed. The bandwidth used in this article is the frequency band that contains sidebands having amplitudes greater than -60dB relative to the transmitted signal. The rate at which amplitude of the sidebands falls off (and consequently the bandwidth) is mainly determined by the shape of the rise and fall time of the dots being sent. The actual keying speed for the same rise and fall shapes has only a minor effect on the bandwidth occupied by the signal, at least for rise and fall times that are only a small portion of the keyed waveform.

We will be analysing the sidebands of the keying waveform before it is used to key the RF waveform. The keyed RF waveform will occupy twice the band width (because it is amplitude modulation) and so key-clicks will extend above and below the transmitter frequency. One further point needs to be made. The shape of the rise and fall of the RF waveform must accurately reflect the waveform that we generate. If the RF signal is modulated early in the transmitter, then all of the following stages must be linear, which for a CW/SSB transceiver they should be. Keying the early stages of a CW-only transmitter using Class-C intermediate amplifiers or PA will "sharpen up" the waveform and destroy the good work that has been done by generating the optimum waveform. A Class-E PA (Ref. 3) is linear in the sense that the amplitude of the RF output is proportional to the supply voltage and so keying it by means of an appropriately shaped supply voltage will maintain the required RF waveform shape.

3. Amplitude of harmonics of the keying waveform

The worst case spreading of a CW signal is when a long string of dots is being sent. Fortunately, this situation is quite easy to analyse mathematically by means of a technique called the Fourier analysis. We can specify a keying speed and the shape of the rise and fall of the RF waveform and derive the amplitude of the harmonics of the waveform. Rather than work my way through the mathematics each time, I compiled a spread sheet that split one cycle of the waveform into 5,000 increments, multiplied each one by the appropriate sine and cosine for each harmonic and summed the result. Some of the rise and fall shapes waveforms were generated using a SPICE simulation program (Ref. 4) and I copied the SPICE output file and pasted it into the spread sheet to give the amplitude of the harmonics for those waveforms.

For this investigation we need to standardise on a keying speed. The Rad Com reviews of new transceivers do not show scope traces of the CW waveform but the ARRL reviews often do, albeit at 60wpm so that the timing relationship between the Morse key operation and RF output can be seen. However, most CW on the HF bands is sent at 30wpm or less and we will adopt this as the keying speed. This corresponds to a dot length and spacing between dots of 40ms giving a period of 80ms and a fundamental frequency of 12.5Hz.

The first waveform that we will consider is a plain on/off switching of the carrier. This keying waveform is shown in Fig 2(a) and the spectrum in Fig 2(b).

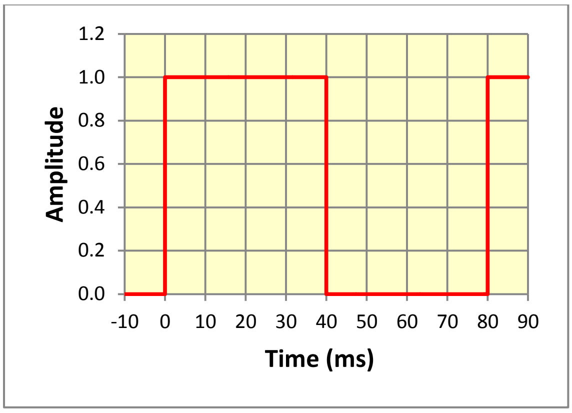


Fig 2(a) Square waveform keying

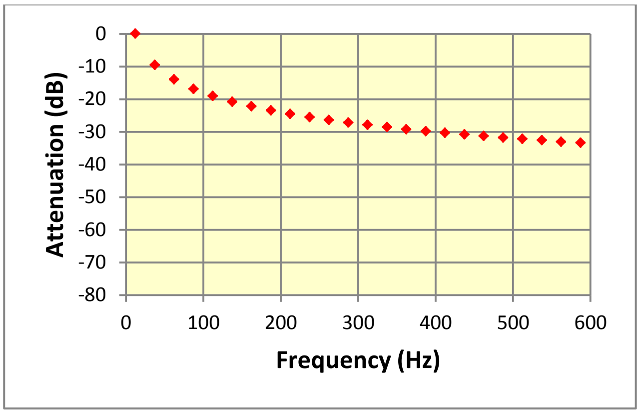


Fig2(b) Spectrum of square waveform keying

This result for a square wave is well known - the harmonics fall off as the inverse of the harmonic number. The third harmonic is 1/3 of the amplitude of the fundamental and the fifth harmonic is 1/5 of the amplitude and so on. So -30dB is reached at 400 Hz, which gives a total bandwidth for -30dB of 800Hz. The harmonics reduce quite slowly with frequency and reach my suggested limit of -60dB at about 12.5 kHz, giving a transmitted bandwidth of 25 kHz. A continuous string of dots has a 1:1 mark:space ratio and such a waveform has no even numbered harmonics. Consequently the above graph shows only odd numbered harmonics. This will also be true of the other waveforms that we will consider.

Another quite well known result is that the harmonics of a triangular wave fall off as the inverse square of the harmonic number. This suggests that slowing down the rise and fall times to turn the waveform from a square wave into a trapezoidal waveform will reduce the bandwidth. So what should be the slope of the rise and fall of the waveform? The ARRL suggests that for a keying speed of 30wpm on a communications circuit with fading, a rise time of about 5ms is adequate and that for a good, non-fading circuit, 10ms is satisfactory. We will look at the requirement for a fading circuit.

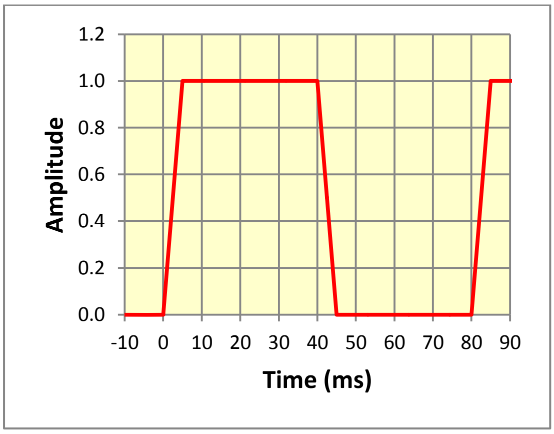


Fig 3(a) Trapezoidal waveform keying

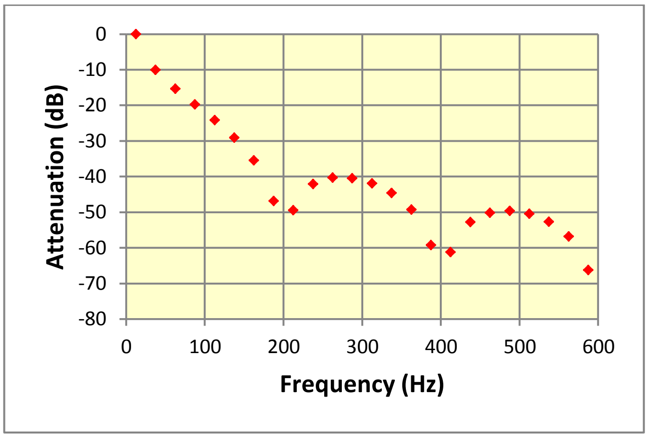
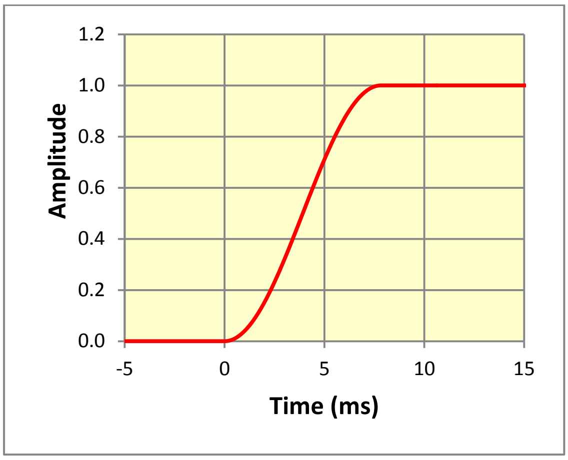


Fig3(b) Spectrum of trapezoidal waveform keying

The trapezoidal keying waveform has a very significant improvement of 20dB over the square wave keying waveform at 500Hz. The problem with this waveform is the sudden changes in slope. If we make the change happen more slowly, then less bandwidth will be required.

We can devise many waveforms which have slower transitions but we need make a decision as to which one to choose. One waveform that has been suggested is the “raised cosine”, which has a rising edge that is the part of a cosine from -180 to 0 degrees and a falling edge that is part of a cosine from 0 to +180 degrees. The slope changes continuously and I have chosen a raised cosine that has a maximum rate of change that is the same as the 5ms ramp above (Fig. 4(a)). For clarity I have just shown the rising edge – the falling edge will be similar.



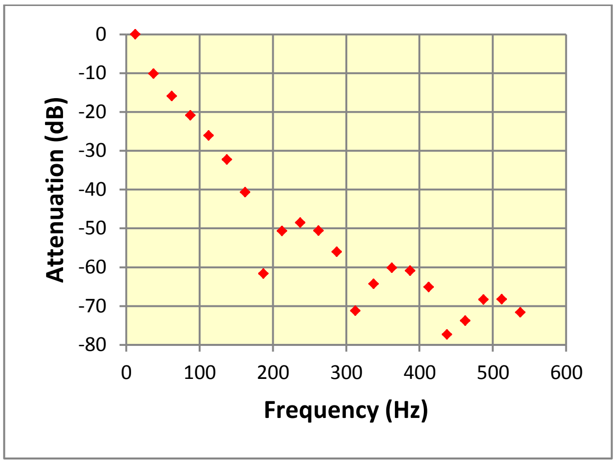


Fig. 4(a) Raised cosine waveform keying

Fig. 4(b) Spectrum of raise cosine waveform keying

As you can see this is a big improvement over the trapezoidal waveform and the -60dB limit that we have set is reached at just under 300Hz, giving a transmitted bandwidth of 600Hz.

Can we do better than this? The answer is that, yes we can, although improvements may be small. On the other hand, if our keying speed is less than 30wpm then we can lengthen the rise and fall times of the keying waveform and this will make a significant reduction to the bandwidth.

As part of this project, I looked at various low pass filters to find one that has an output response to a step input (i.e. keying the input to the filter) that approximates to a raised cosine. I used SPICE to simulate these filters and copied the output file into an EXCEL spreadsheet that had the values for a raised cosine. I found that a filter with an output that closely matched a raised cosine is a four pole transitional Gaussian to 6dB low pass filter. The output of this filter and a raised cosine is shown below.

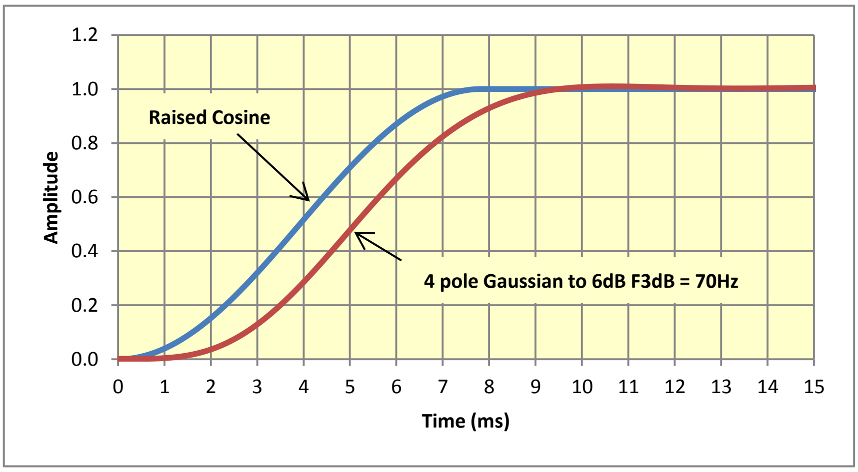


Fig. 5. Comparison of 4 pole Gaussian to 6dB filter with a raised cosine

The part of the Gaussian response between the amplitude 0.1 and 0.9 is a close approximation to the raised cosine with a maximum slope equivalent to the 5ms ramp but with an additional delay of about 1.2ms. The initial rate of change is less and the so required bandwidth is less. This Gaussian response is particularly attractive because it has almost no overshoot.

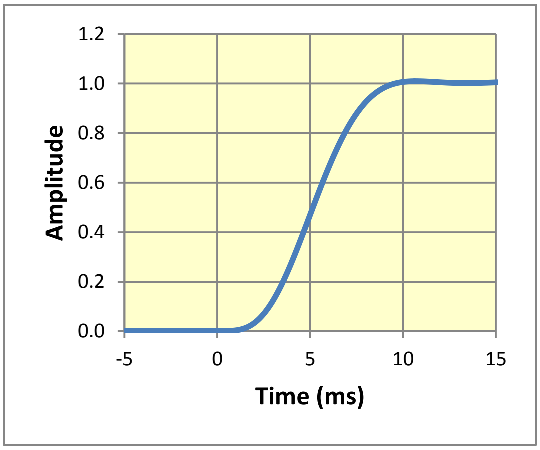


Fig. 6(a) Gaussian waveform keying

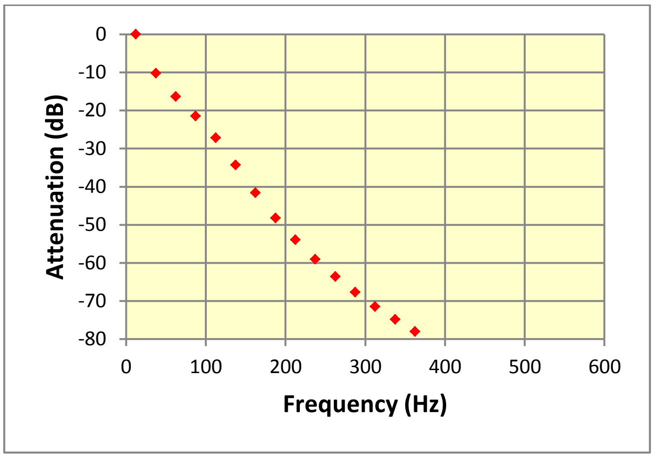


Fig. 6(b) Spectrum of Gaussian waveform keying

The harmonics are below -60dB above 230Hz, which gives a transmitted bandwidth of 460Hz. We have followed the ARRL recommendation for 30wpm and a fading communication channel. If we key the transmitter at a slower rate (I prefer 20wpm or less), then we can scale the filter component values, decreasing the shaping filter -3dB frequency to perhaps to 35Hz.

4. **Transients caused by the keying waveform**

So far we have looked at the frequency spectrum of a continuous string of dots. We have seen that this can be analysed into a series of discrete frequencies that are multiples of the dot frequency. So it might be thought that if we tune a receiver either on the high side or low side of a CW signal that we will hear various audio tones due to these discrete frequencies. If the bandwidth is very narrow (a few Hertz), then we will hear a tone corresponding to one of the harmonics but in practice the bandwidth of receivers is much wider and a number of harmonics will be received. CW IF crystal filters often have bandwidths of 500Hz to 250Hz, although a receiver with digital processing may allow bandwidths of 200Hz or less to be used.

Let us imagine a receiver fitted with a 200Hz bandwidth IF filter with a good shape factor, tuned to a frequency 1kHz away from a CW station, so that we are just receiving the harmonics of the keying waveform that are between 900 and 1,100Hz away from the transmitting signal. We will demodulate the signal by placing our BFO exactly on the CW station's frequency. The response of the IF filter is effectively mapped down to audio. We can use SPICE to investigate what happens in the time domain.

We need to simulate an AF band pass filter that approximates to a typical IF filter response mapped down to audio. I designed a loss-less 5 pole Chebychev band pass audio filter with 0.1dB ripple and a 200Hz bandwidth at a centre frequency of 1kHz. This filter (Fig. 7) uses both series and parallel resonators to obtain a symmetrical response (when plotted against log-frequency). Fortunately, SPICE doesn't concern itself with whether such a filter can be easily constructed.

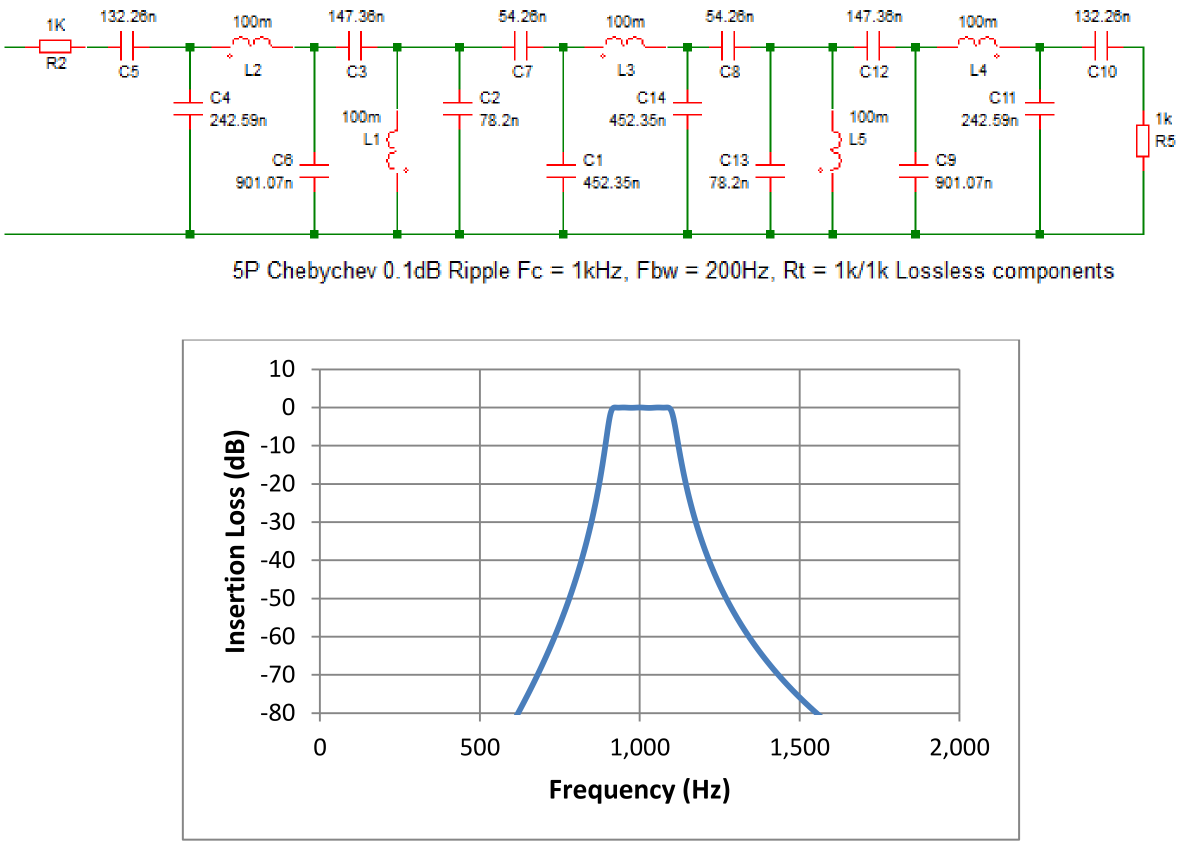


Fig. 7. Audio filter circuit and response

The group delay of the filter is about 6ms at the centre frequency, rising to about 12ms at the edges of the passband. A change in the input waveform will take several milliseconds before its effects are seen at the output.

The keying waveform, which for this exercise will be a trapezoid with 10ms rise and fall times, is applied to the input of the filter. SPICE predicts that the output of the filter will be as shown in Fig. 8. I have attenuated the keying waveform by 1,000 times so that both the input and the output can be displayed on the same graph.

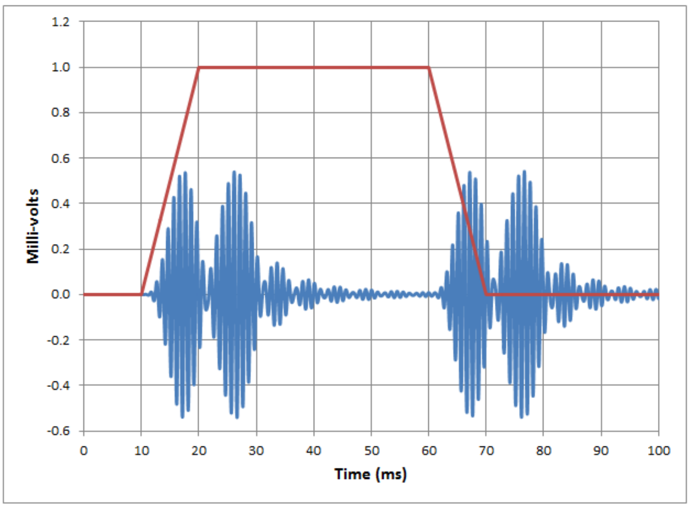


Fig. 8 Keying waveform (with an attenuation of 1,000 times) and filter output

The output of the filter is not continuous and demonstrates why clicks and not tones are heard when the receiver is tuned away from a strong CW station sending a string of dots. The reason why I chose a keying waveform that is a ramp is to show that the key-clicks are generated when there is sudden change in the waveform. There are two sudden changes in slope of the rising and falling edges and each generates a transient. By smoothing out these sudden changes in slope, the amplitude of the transients can be reduced.

An SDR receiver divides the spectrum into a large number of contiguous narrow band segments. If the width of each segment is several times the keying rate, then those close to the frequency of the CW transmitter will contain energy from the transients caused by the rise and fall profile of the keying waveform and will be displayed as a horizontal line (see Fig. 1).

5. A practical transitional Gaussian to 6dB filter

I obtained pole positions for the transitional Gaussian to 6dB low pass filter from Ref. 5. This book contains tables of both pole positions and component values normalised to 1 rad/sec. The required response can be obtained using two cascaded Sallen-Key active filters (Ref. 6) with suitably scaled component values. I took the pole positions for the four pole filter from the table and calculated the resistor values for preferred capacitor values. A filter with a -3dB frequency of 70Hz is shown below.

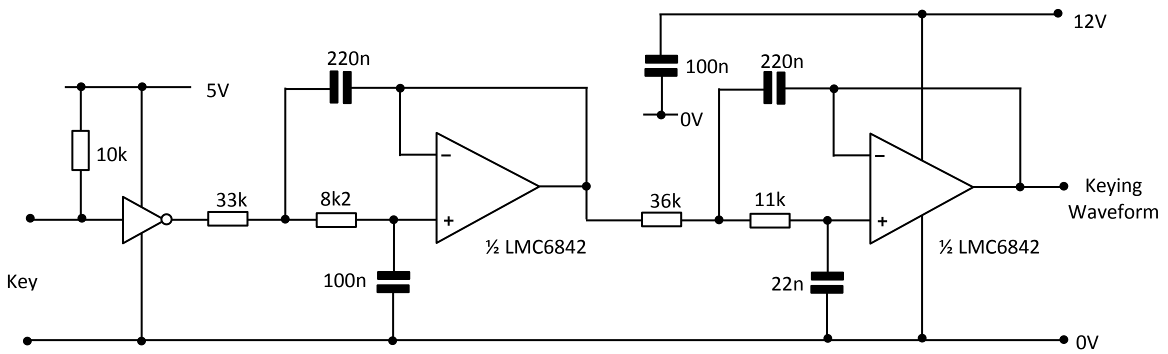


Fig. 9. Four pole transitional Gaussian to 6dB low pass filter with a -3dB frequency of 35Hz

The LM6482 is a dual rail-to-rail input and output operational amplifier and is used so that the circuit will run from a single polarity supply. As shown, the input to the filter is from a CMOS gate and switches between 0V and 5V when the key is pressed. The output can be amplified or attenuated as required.

6. Practical results

I made a crystal oscillator/diode double balanced mixer/low pass filter as a very simple direct conversion receiver and fed the output into the audio channel of my netbook running Spectrum Lab software. A function generator set to 12.5Hz (equivalent to 30wpm) keyed a breadboard 10MHz QRP TX with a Class-E PA. The first spectrum is with straight on/off keying without shaping.

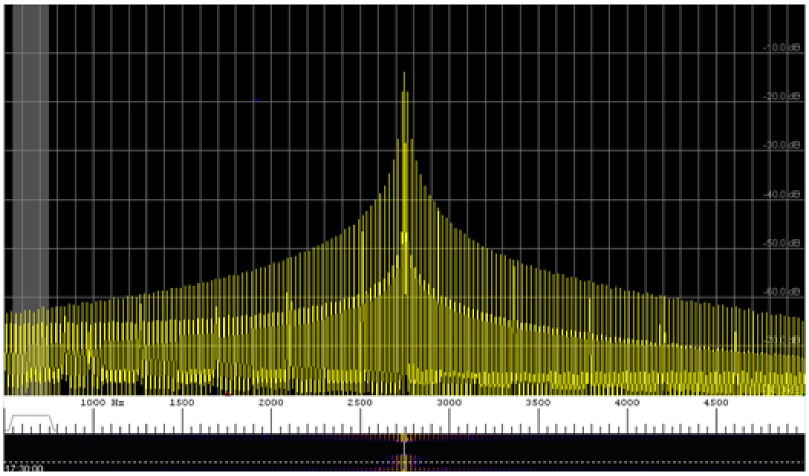


Fig. 10. Spectrum with plain on/off keying, no shaping

The supply voltage was then shaped by a four pole transitional Gaussian to 6dB low pass filter with a cut off frequency of 35Hz. This filter has a maximum rate of change of half that shown in Fig. 6 and is better suited to my preferred keying rate is 20wpm or less.

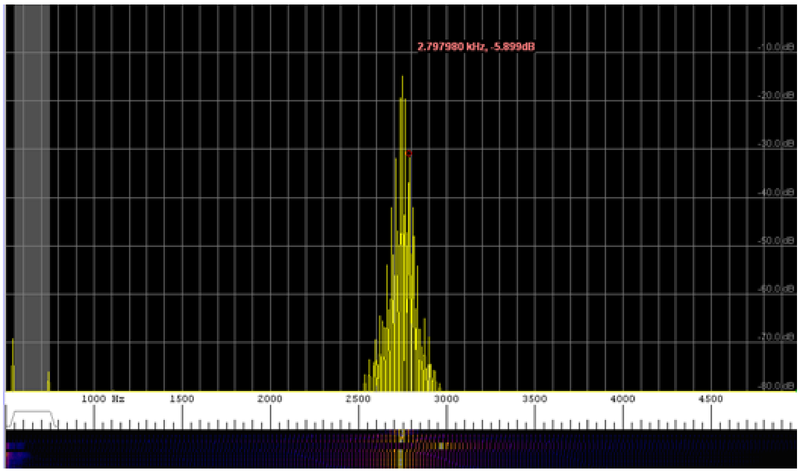


Fig. 11. Spectrum with 4 pole Gaussian to 6dB filter with 35Hz cut-off frequency

The improvement needs little in the way of comment. The -60dB bandwidth is of the order of 300Hz.

7. Commercial transceivers

INRAD (a US crystal filter manufacturer) has published a report (Ref. 7) about a modification to the Yaesu FT-1000MP to reduce the effects of key-clicks generated by this rig. It seems that the FT-1000MP has gained a reputation for generating key-clicks. The INRAD report includes transmitted frequency spectra before and after the modification and also for several other transceivers.

The INRAD report also notes that a Gaussian filter would have greatly improved the situation but for the FT-1000MP a significant cause of the excessive sidebands is the non-linearity of a FET that keys the transmitter.

Reviews of transceivers published in QST often include spectrum analyser displays of the output keyed at 60wpm.

Some commercial transceivers are tackling the problem of excessive sidebands by user selectable rise and fall times, for example the Kenwood TS-590 and the Icom IC-7300. A review of this latter transceiver by Adam Farson VA7OJ/AB4OJ (Ref. 8) has a number of scope and spectrum images of the keyed RF waveform for various rise and fall times.

8. Conclusion

The best profile for CW that I found was that generated by a four pole transitional Gaussian to 6dB low pass filter. This is better than a raised cosine and easier to generate. However, it is essential that linearity is maintained and that the output waveform follows the output of the Gaussian filter. Many PA circuits that are used for CW, for example Class-C may not be suitable.

9. References

1. ARRL Handbook 2004 Figure 12.21 (this graph may be reproduced in later editions of the Handbook).
2. RSGB Band Plan 2016, Radio Communication, March 2016
3. Nathan O. Sokal WA1HQC, “Class-E RF Power Amplifiers”, QST January/February 2001
4. http://www.simetrix.co.uk/site/simetrix-classic.html - this is a free evaluation but fully functional SPICE simulator. It limited to about 140 nodes.
5. Arthur B. Williams and Fred J. Taylor, “Electronic Filter Design Handbook”, McGraw-Hill. This is one of my favourite filter design books, much more readable than “Handbook of Filter Synthesis” by Zverev, which is the standard work on filter design. It also covers low frequency op-amp filters and the book contains many tables of filter design constants.
6. https://en.wikipedia.org/wiki/Sallen%E2%80%93Key_topology
7. https://www.**inrad**.net/files/Pubs/About%20Key%20Clicks.pdf
8. http://www.ab4oj.com/icom/ic7300/main.html

Appendix. Keyed output waveform for two commercial transceivers owned by the author

1. **ICOM IC-7000**

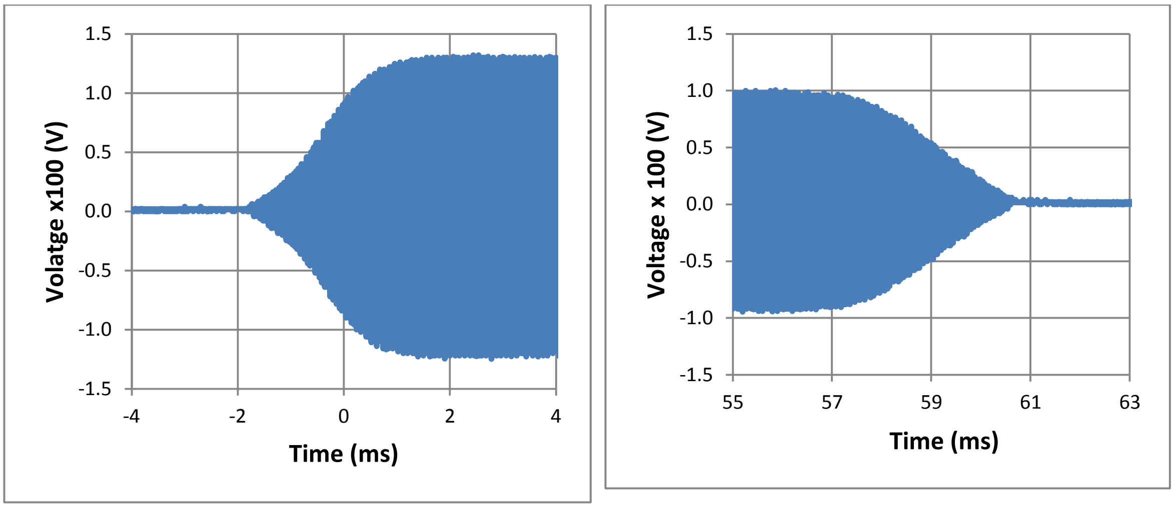


Fig A.1 IC-7000 keyed at approximately 20 wpm, 100% power at 10.106MHz

The time axis is not related specifically to start or end of the keying waveform. This transceiver has quite gentle transitions, although the rise and fall times are faster than necessary for my preferred CW speed. The RF voltage at the start of the CW dot is greater than at the end of the dot. This may be due to the regulation of the switching power supply used for this test. The QST review (May 2006) has a spectrum analyser display of CW sent at 60wpm with a power of 100W and shows the bandwidth at -60dB to be about 1kHz.

2. **Kenwood TS-530S**

This transceiver is more than 30 years old and was one of the last of the hybrid rigs - solid state except for the PA and its driver.

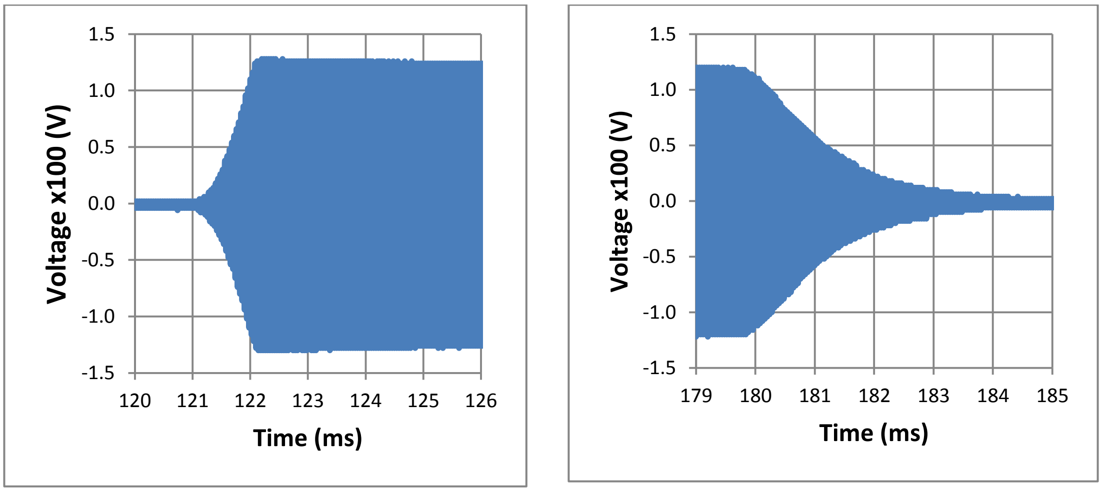


Fig A.2 TS-530S keyed at approximately 20 wpm, 100% power at 10.106MHz