Cable bundling

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Abstract

This paper presents measurements of the effect on common-mode impedance of a variety of different ways of "losing" spare cable length within an EMC test set-up. These ways include not only several versions of "bundling" but also "meandering" and a novel configuration suggested by the Viper at London Zoo.

It is known that resonance in conventional cable arrangements seriously disturbs test results at or near the resonant frequency.

Such resonance will be clearly seen in most of the representative impedance vs. frequency characteristics that will be presented. The configurations tested will be interpreted in the light of simple circuit theory.

It will be shown that surprisingly simple improvements to "bundling" – even within the context of existing Standards – minimise or eliminate resonance and so should result in dramatic improvements in EMC test reproduceability.

1) Introduction

Last summer I visited London Zoo and in the reptile house I saw an interestingly-coiled Viper. It had arranged itself as shown in the rope model of ***Figure 1***.

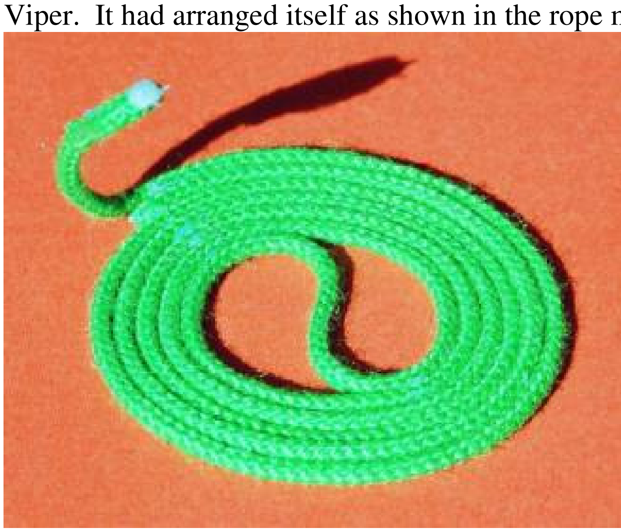

Figure 1 A rope model of an interestingly-coiled Viper.

It appeared to want to keep close to itself – but was limited in what it could do by its body bend radius. These are the same constraints that apply when trying to minimise the effect of surplus cable during EMC test. Earlier work (*reference 1*) has shown that cable resonance has a dramatic effect on radiated field emission (and presumably on immunity) at and near the resonant frequency. Therefore inductance must be minimised so as to raise the resonant frequency and reduce its "Q" value. When excessive cable length is presented with the equipment for test the choice is between cutting the cable short and folding or coiling it in some way. Some purists argue that "any old bundle" should be used because that is what would be used in the practical application of the EUT. However this argument should not be applied within an EMC test chamber or between EUT and LISN since that is necessarily an artificial situation, and within that context the correct objective is to minimise the variation due to cable layout.

Minimum common-mode inductance is achieved by folding the cable back on itself as closely as possible. This technique was first applied more than a hundred years ago as the "Ayton-Perry winding" for non-inductive resistors – but in EMC applications perfection is limited by the permitted bend radius of the cable. This paper confirms previous work (*references 2, 3, 4*) on the performance of cable "bundles" and "meanders" as are in common use today, compares these with the Viper's configuration, and describes various improvements.

2) Measurement method

To avoid errors due to EUT or chamber configuration all the measurements in this paper are of $|S_{21}|$ in common mode of the target configuration of a 1.5m length of cable secured onto a cardboard rectangle and held 100mm above a ground plane. $|S_{21}|$ may be thought of as the loss due to the cable stretched between 50 ohm terminations. Accordingly an $|S_{21}|$ of -6dB equates to a halving of the voltage and so to 100 ohms series impedance if resistive.

The measurements on these cables are presented here in comparison with $|S_{21}|$ of a 310mm length of cable between the same two Vector Network reference planes; ie each method of cable shortening is analysed for a 1.19m reduction in length.

Figure 2 In the test set-up the VNA reference planes are at the connectors on copper strip brackets.

In the test set-up shown in ***Figure 2*** the VNA reference planes are at the connectors on copper strip brackets that may be seen to the left and right of the 0.31m cable. Crocodile clips were soldered to these connectors for quick replacement of the cable on test. RG58 coaxial cable was used for all the tests because it was readily available and because, since the tests are of common-mode impedance, the actual cable core arrangement was unimportant. The crocodile clips were connected to the cable shield: In the tests reported here no connection was made to the cable inner conductor.

3) Contemporary meanders and bundles

Figure 3 shows the test meander.

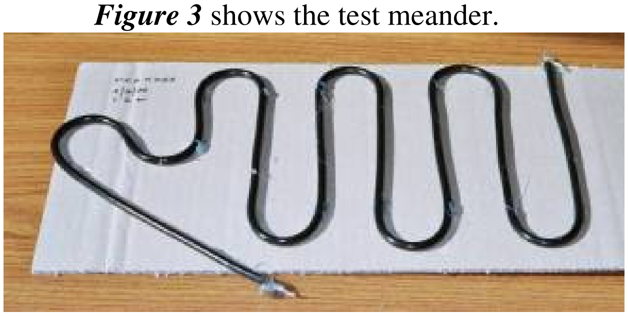

Figure 3 The test meander cable.

Note that care has been taken to keep the meanders apart so as to maximise the frequency at which resonance of the loops will occur. The impedance is shown in ***Figure 4***, where the meander impedance is in blue with the 0.31m reference cable impedance for comparison in green.

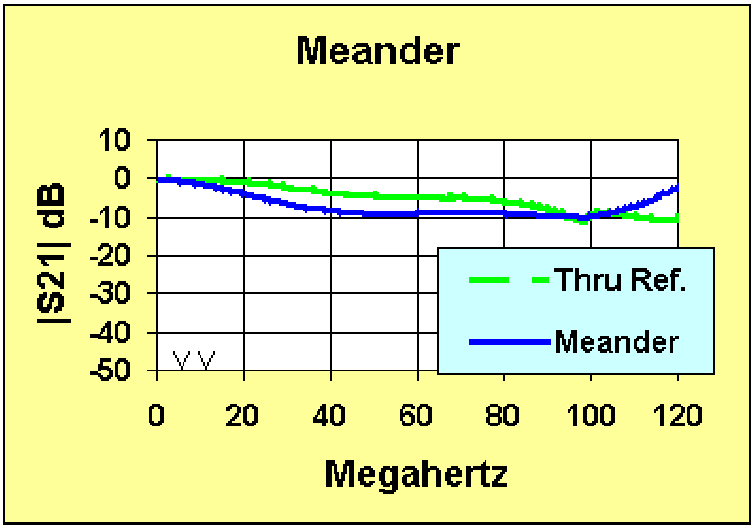

Figure 4 The impedance of the arrangement in the previous figure in blue with the 0.31m reference cable impedance for comparison in green.

The meander shows a higher impedance at low frequencies, and a lower impedance than the reference above 100MHz as it approaches its first series-resonant frequency (which is 149MHz; - which was outside the range of the VNA used here). Studies of these higher frequency resonances using the measuring method of *reference 5* showed impedance minima at 149 and 215MHz and maxima at 190 and 260MHz. Separate as-yet unpublished work by the author has shown that to obtain a smooth impedance frequency characteristic the dimensions of a meander must be tapered. The meander does appear to be a good way of "losing" cable *but only if the cable is well spaced apart to minimise inductive and capacitive effects*: A "squashed meander" has just the same problems as the bundle that is considered next. Another difficulty with the meander is of course the large amount of space it requires.

Figure 5 A "traditional bundle" wound with the end loops inductively *adding*.

Figure 5 shows a."traditional bundle" (again, of 1.5m length) with the end loops inductively *adding* – that is, with any low-frequency common-mode current going in the same direction in adjacent loops. This is the configuration that arises naturally if one makes a large coil of cable and then squashes it and tapes the middle section. The impedance is shown in

Figure 6.

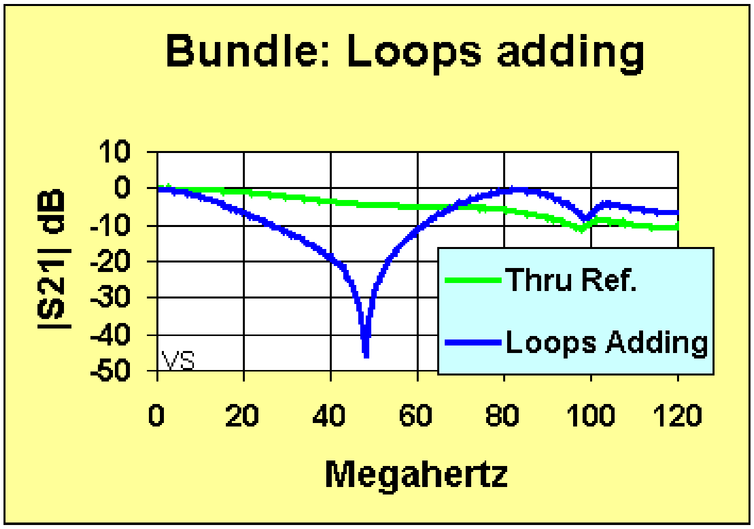

Figure 6 The impedance of the arrangement in the previous figure with the 0.31m reference cable impedance for comparison.

Here we see the problem with bundles; there is an extremely strong resonance at 48MHz that would drastically reduce the emission/susceptibility for cable-borne interference at that frequency. The resonance is that of the loop inductance tuned by the capacitance between the cable runs through the taped section. Similar resonance effects have been noted before (*see references 2, 3 and 4*) and it is certain that they are present in all cable bundles unless special precautions are taken.

4) Improved bundles

The most obvious improvement to a bundle is to *turn over alternate loops* and tape them tightly together so that their magnetic fields oppose each other.

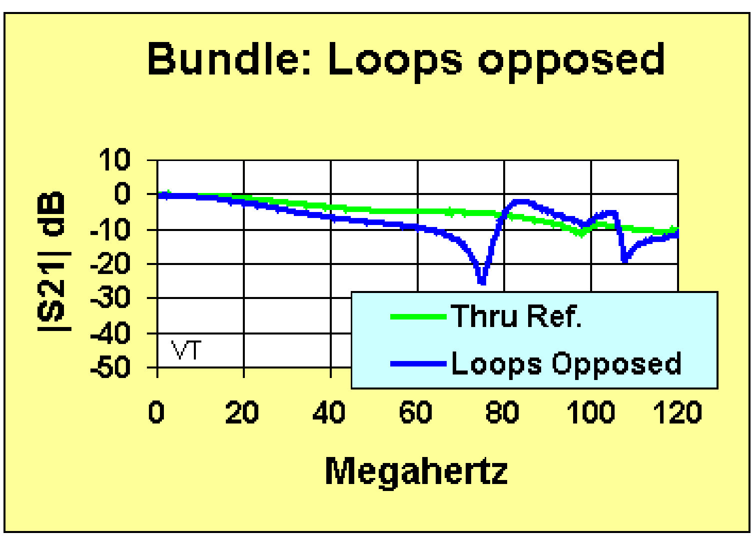

Figure 7 The dramatic improvement produced to the arrangement of Figure 5 by turning over alternate loops.

This produces the dramatic improvement shown in ***Figure 7***, moving the resonance to a much higher frequency and reducing the depth of resonance from 42dB to 20dB. Note that the resonance has split to two frequencies, just as it would in the "IF transformer" of a radio receiver if the two tuned circuits were too tightly coupled.

It takes practice to wind a bundle this way, and the method only works at all if there are an even number of loops at each end, but the improvement is very worthwhile and the cost is nil.

Clearly further improvement would be possible if the "Q" factor of each loop could be reduced. There are two possible ways to do this.

The first way is to clip a ferrite ring over each end loop-pair of the bundle, as shown in ***Figure 8***.

Figure 8 A ferrite ring may be clipped over each end loop-pair of the bundle of Figure 5.

This almost completely removes the resonances as may be seen in ***Figure 9***.

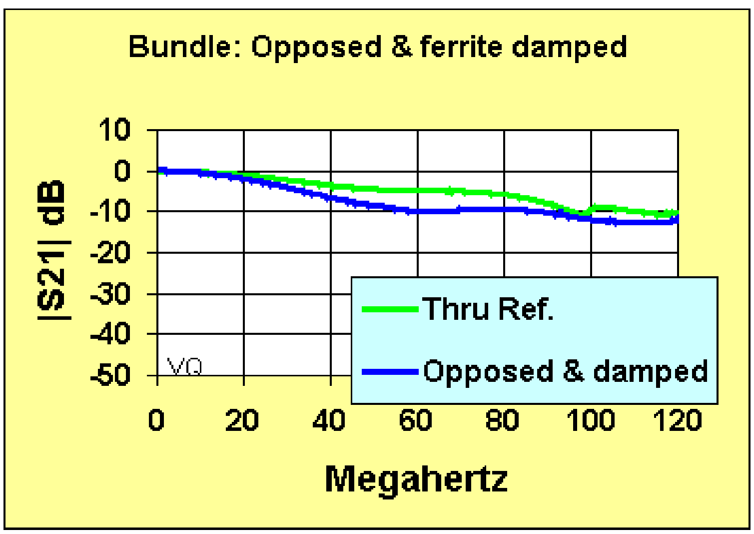

Figure 9 The ferrite rings almost completely remove the resonances.

Since each ferrite encompasses two loops in which low-frequency common-mode current flows in opposite directions there is no gross effect. This appears to be a novel way to use a ferrite ring: The opposing current flow in each loop means that not only is the ferrite free from risk of saturation by unbalanced current flow but also the magnetic permeability of the core does not transfer any series inductance to the cable at low frequencies. Never the less the core provides very effective damping of high-frequency resonance.

This use of ferrite-loaded opposing loops provides a very satisfactory non-resonant bundle – but note that its worst frequency is 60MHz where $|S_{21}|$ is still 5dB worse than the reference.

The second method of damping is to add *resistively-loaded* loops closely coupled to the cable loops as shown in ***Figure 10***.

Figure 10 The second method of damping is to add *resistively-loaded* loops closely coupled to the cable loops.

Here, at each end the two loops are wound so as to be opposing as before *and* their residual inductance is damped by a single turn of copper foil with a 22 ohm resistor in series.

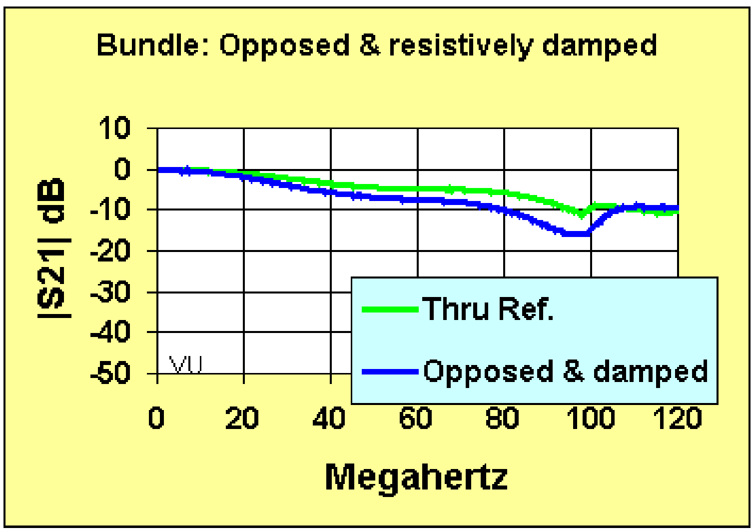

Figure 11 The impedance of the arrangement in the previous figure shows a dramatic improvement.

Figure 11 shows the result - an equally dramatic (but different) improvement. There remains some trace of resonance around 95MHz that may only be improved by tighter inductive coupling of the damping loops. At 60 MHz $|S_{21}|$ is only 3dB worse than the reference. This is better than the ferrite-damped arrangement reported above. Below 70 MHz $|S_{21}|$ is lower than that of the meander – and of course the bundle is much more compact than is the meander.

Figure 12 A "practical" version of the resistively-loaded opposed-loop bundle.

Figure 12 shows a "practical" version of the resistively-loaded opposed-loop bundle. It is intended for mounting on the frame of a table in an EMC test chamber by its (black) brackets and is made almost entirely of non-conductive materials. This unit can accommodate any length of 5mm diameter cable between 1.3 and 6.4m. The loops are formed around (blue) drums of the desired bend radius and the straight section held together by further drums that may be cammed in to hold the cable tightly. The right hand drum assembly may be loosened from the (brown) Tufnol rod and slid according to the length of cable that it is desired to "lose".

Figure 13 Details of the "practical" version.

As shown in ***Figure 13*** the "opposing loop" configuration is obtained by applying the rule that all cable runs from left to right cross over to the other side of the drum at the other end, whilst all cable runs from right to left go to the ***same*** side of the distant drum. The arrows on the label remind one of this. On the RH drum may be seen the glint of the copper damping turn. Its ends are bridged by two 47 ohm resistors in parallel. The RH drum also has a bevelled flange to retain the cable. Results are identical to those in ***Figure 11***.

The author was introduced to a different form of traditional "bundle" by a member of a UK standards committee. This arrangement has the advantage that it "uses up" the desired amount of cable in a very intuitive way. The first step towards this arrangement is shown in ***Figure 14***.

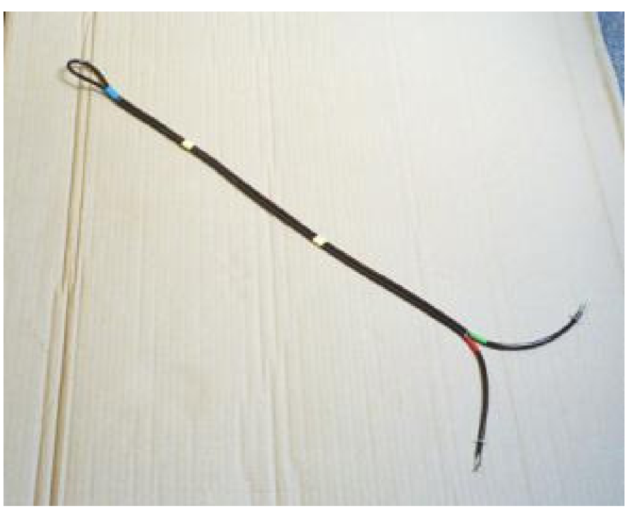

Figure 14 The basis of a different form of traditional bundle that uses up the desired amount of cable in a very intuitive way.

A 1.5 m length of cable identical to that used throughout this series of tests is reduced to a 0.31m connection in the form of two 0.155m "tails" from the red and green sleeves to the cable ends. The remaining cable is folded into a loop that is secured by the blue tape at the centre of its length, and the bulk of the cable is taped together tightly with narrower yellow tape.

This length is then folded into three.

Figure 15 The second fold of the above bundle.

From the intermediate stage shown in ***Figure 15*** it can be seen that the final result is going to be a bundle with three turn loop at the LH end and a two-turn loop at the RH end where the EUT and AE cable ends peel off.

Figure 16 The cable tightly tied to complete the above bundle.

Figure 16 shows the cable tightly tied whilst preserving the desired minimum bend radius. This bundle has the $|S_{21}|$ characteristic shown in ***Figure 17***.

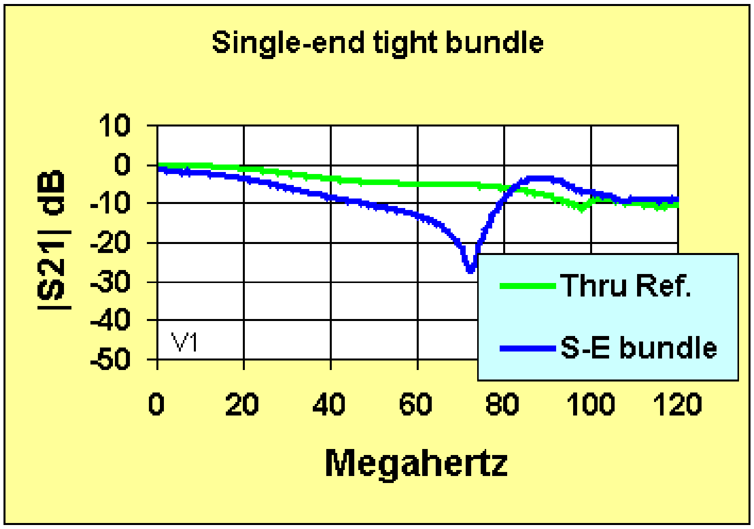

Figure 17 The impedance of the arrangement in the previous figure.

The resonant impedance at 72MHz is at –22dB; better than the conventional bundle but not very good. This is to be expected since there are *three* loops at one end so only two can cancel each other whilst the third is freely resonant. Some additional measurements (not presented here) showed that ferrite damping can get rid of the resonance but seriously degrades performance at 40MHz because the ferrite inductance is in series with this unbalanced third loop. Resistive loop damping is quite successful; it reduces the resonance to –10dB without having any bad effect at 40MHz. Tests of a similar but "loose" bundle showed a –28 dB resonance, showing once again that it is always an advantage to bind opposed bundles tightly.

The *virtue* of this single-ended bundle is that once folded in half any further loops are necessarily paired with loops with current flow in the opposite direction. The *problem* is that the initial centre-loop has no other single loop against which it can be placed to counter its inductive effect.

Figure 18 The basis of an improved version of the bundle of figure 14.

However, we can avoid this problem by introducing another loop at the cable-tail end. This can be achieved by making the initial fold as shown in ***Figure 18*** where (in contrast to the arrangement in ***Figure 14)*** there is an additional loop near the "tails".

Figure 19 The second fold of the above bundle.

As shown in ***Figure 19*** the centre loop can then be brought into close opposition to this added loop.

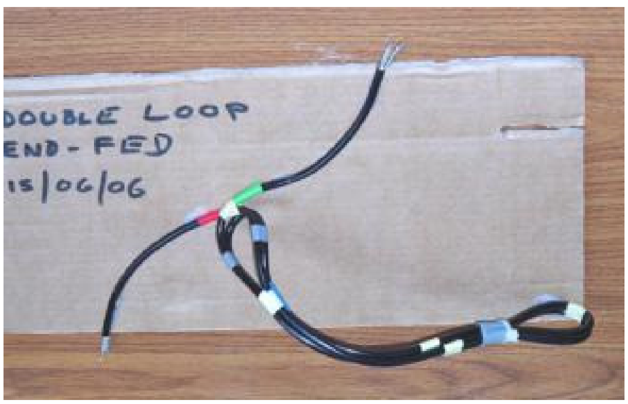

Figure 20 The cable tightly tied to complete the above bundle.

When taped into a tight bundle (***Figure 20***) the $|S_{21}|$ characteristic of this is as good as any other opposed-loop without additional damping – see ***Figure 21***.

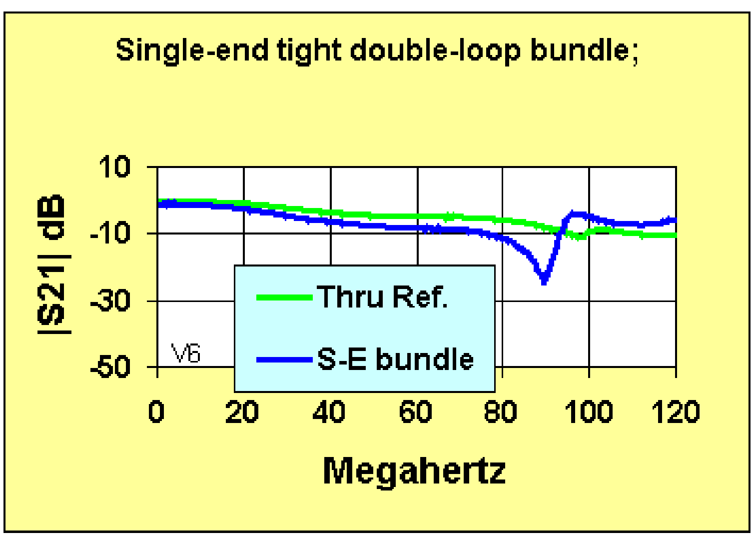

Figure 21 The impedance of the arrangement in the previous figure.

However since its ends are both double loops it should be possible to apply ferrite damping as in ***Figure 22*** without any ill effect.

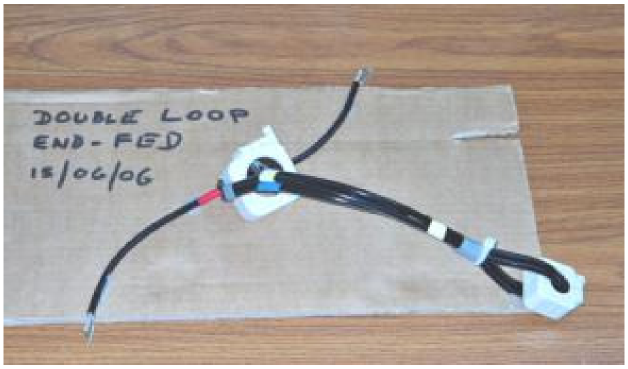

Figure 22 Ferrite damping added to the improved bundle of figure18.

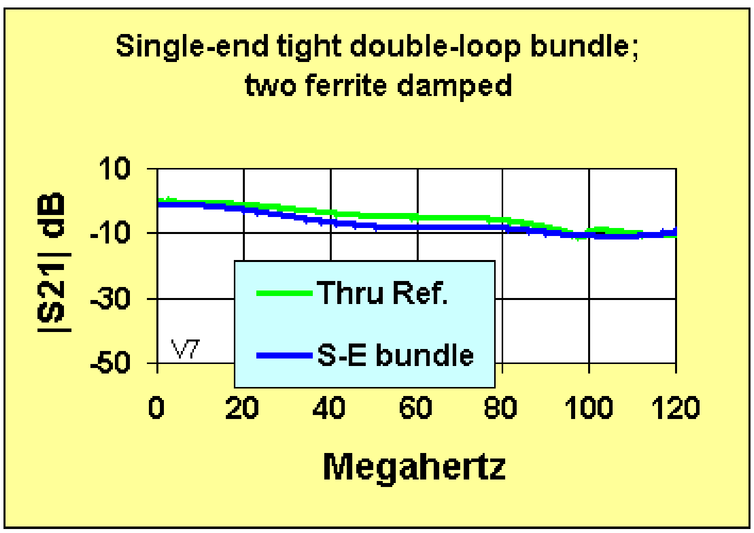

Figure 23 The very satisfactory impedance of the arrangement in the previous figure.

Figure 23 shows that this is true: This configuration "loses" 1.19m of cable whilst exhibiting a maximum change of $|S_{21}|$ of less than 5dB. This is the best performance obtained in this series of tests. It results from a bundling process that is easy to apply, and which only requires care in the placing of the centre loop over the tail loop in the correct phase.

5) The viper

A "Viper" made with 1.5m of cable is shown in ***Figure 24***.

Figure 24. A “Viper” made with 1.5m of cable.

Topologically this resembles the configuration of ***Figure 14***, and its basic impedance characteristic (***Figure 25***) is much better than the conventional bundle of ***Figure 6*** .

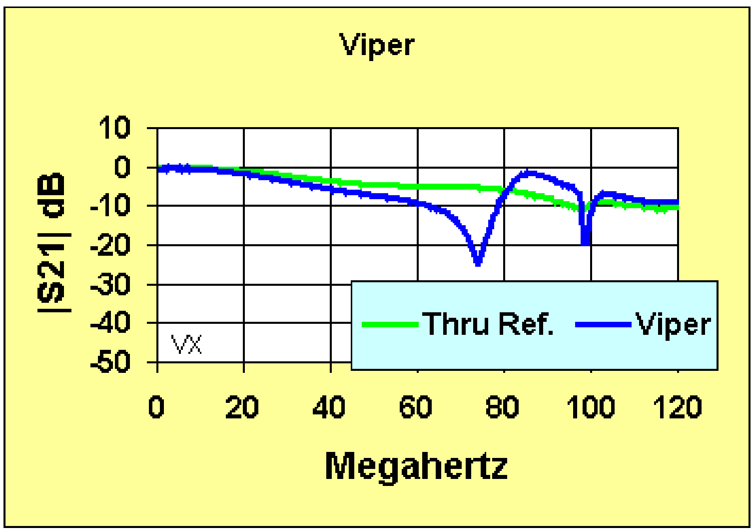

Figure 25 The impedance of the arrangement in the previous figure.

However there is only one practical way to improve it; that is to clip a single ferrite ring across the centre of the viper. This has the effect shown in ***Figure 26.***

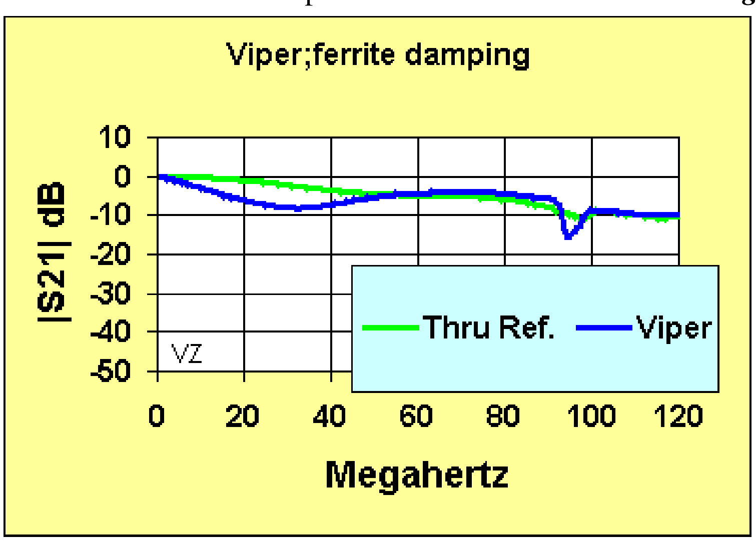

Figure 26 The impedance of the “Viper” with a single added ferrite ring.

The high-frequency resonances are removed but because the ferrite encompasses only a *single* pass of the cable it is ***in series*** with low frequency common-mode and so causes a 6dB degradation at 30 MHz relative to the reference cable. The same effect had been observed when the three-loop bundle in ***Figure 16*** was loaded with ferrite.

Furthermore it is not easy for us mere humans to arrange a tight double spiral. The Viper's idea has yet to justify it's use in EMC testing – but it did get the author thinking!

6) Conclusions

* A meander is better than a bundle, but *only if it is very wide-spaced and hence bulky*.

* A bundle may be greatly improved by having *only opposed pairs of loops* at each end.

* The most convenient bundle shape to meet this requirement is that of ***Figure 20***.

* The addition of ferrite rings as shown above in ***Figure 22*** and diagrammatically in **Figures 27, 28 and 29** produces a bundle that is at least as good as a wide-spaced meander but occupies much less space. It can be strongly recommended for general use in EMC testing.

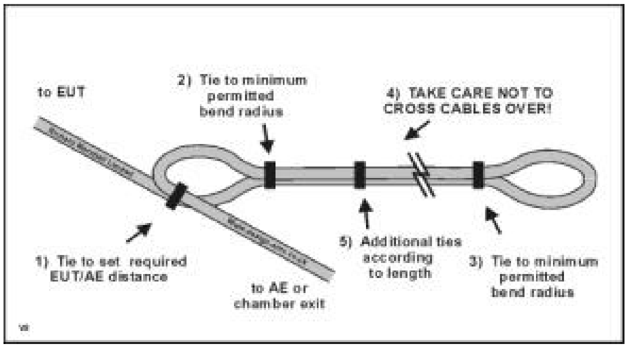

Figure 27 Optimum bundling; stage 1

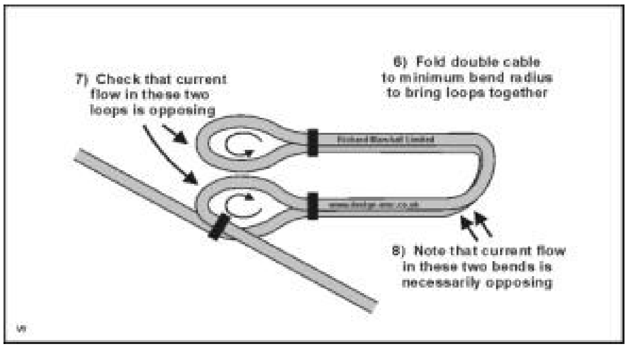

Figure 28 Optimum bundling; stage 2

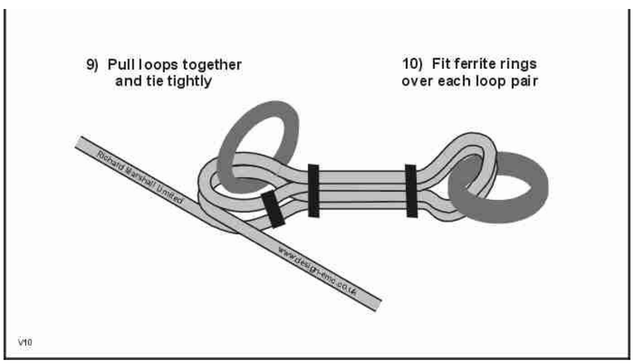

Figure 29 Optimum bundling; stage 3

7) Acknowledgements

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8) References

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