Dear Les,

First of all I hope all is well and business is good.

Just to let you know I have finished my studies and graduated with a 2:1! which I was delighted with. I am also contacting you to thank you again for the provision of materials for my project. I will also send you a hard copy and a copy on CD by post of a small report I have put together covering the major aspects and conclusions from the final report basically showing what I carried out and I what I found. It includes graphs, tables and some frequency responses which I hope you find useful. By the way my results were very good in terms of the performance of the SDS when compared to the undamped samples as you will see.

Thanks again

Richard Johnson

Sound and Vibration Control using Sound Dead Steel:

Extract (from thesis):

An investigational paper is presented with the aim of studying the effects of a viscoelastic layer constrained by sheet steel (such as Sound Dead Steel) of different geometry, with regards to improving the damping and noise reduction within structures. Viscoelastic layers come in the form of very thin polymers or adhesives that when constrained by a material such as steel enhance damping by dissipating impact energy through shear due to their low Young's Modulus. In today's environment the reduction in noise and vibration of appliances is in high demand not only for more comfortable surroundings but also to reduce fatigue within structures. This paper is an investigation into how viscoelastic damping improves these factors and by what quantity when compared to normal sheet steel of the same geometry. Therefore by utilizing a range of experimental evidence to obtain an indication to an area where viscoelastic damping is most beneficial. The evidence is based upon impact vibration and sound measurement, obtaining damping ratio and sound pressure levels whilst a comparison of these results is made with FEA modeling.

Project Overview:

The following is a brief breakdown of the major aspects covered and concluded from the project, with the majority of the text and graphs taken directly from the final report.

Project Method:

I carried out five experiments along with theoretical analysis (FEA) using the four samples kindly donated and compared the two SDS damped samples (bar and plate) to the two undamped normal steel bar and plate of the same geometry, to investigate how they compared in terms of damping and noise reduction. A brief breakdown of each experiment is described as follows:

Test 1: Damping Test

The initial experiment entails the testing of the four samples, by clamping each of them in turn at one end, leaving the majority of the sample free, therefore a cantilever is produced to simulate exactly the FEA models created. Each sample is tested individually analysing the frequency response of the plate via the accelerometer, connected to a charge amplifier which amplifies the acceleration through to a FFT Spectrum Analyser, which creates the image of the response on a display screen showing different resonances. Therefore the response can be printed and analysed, and the natural frequencies of the samples can be obtained. The accelerometer is mounted at the end of the samples, furthest away from the clamping area or the end with the most displacement and acceleration. The accelerometer is mounted to the plate using Beeswax. An impact hammer will be used to impact the samples. All impacts will be applied to the same end of the plate to where the Accelerometer is mounted.

Test 2: Transmission loss

This experiment is only applicable to the SDS plate when compared to the normal plate. The sample is placed centrally onto the speaker, which dissipates the white noise produced from the noise generator. Creating a direct path of transmission noise through the plates ensures no noise radiation is lost through gaps. All transmission tests are one minute in duration. The microphone is placed in the Free Field position at the centre of the sample and at a distance of 10mm above the sample.

Test 3: Impact Test

Again this experiment is only applicable to sample plates. Both samples are situated in the same clamp that is used for the damping experiment, so that the same conditions apply and a cantilever is produced. The experiment entails impacting the samples with two types of balls of different diameter and mass, from a set height of 535mm. The microphone is placed on its tripod at 45 degrees, 275mm above the samples.. Each ball is dropped three times from the set height onto the centre of the sample. With the microphone spectrum set on max mode, to enable only the maximum sound radiated from the impact to be recorded.

Test 4: Additional Vibration Test:

Further vibration tests are carried out on the SDS and normal steel plate, which consist of impacting the plates with the impact hammer when positioned as in the transmission loss experiment. Hence, each plate is sat on the speaker with the accelerometer attached to their centre; the plate is then impacted to investigate where the plates resonate and if it correlates with any peaks that may occur from the transmission loss experiment data.

Test 5: Additional Impact Damping Test:

For the impact vibration damping test on the SDS plate and normal steel plate, the set up will be as found in Test 3 (without microphone), but positioning the accelerometer at the centre of the samples when impacted as close the centre as possible with the ball bearing only. Thus investigating the reduction in acceleration or amplitude between the two samples when they are impacted using the FFT Spectrum Analyser.

Project Findings:

Note Sample 1 = Normal undamped steel plate

Sample 2 = SDS plate

Sample 3 = Normal undamped steel bar

Sample 4 = SDS bar

Test 1: Damping test, FEA comparison and damping ratios:

The comparison from the FEA study to the experiment shows that the natural frequencies found in both cases were extremely close. Hence the accuracy of the experiment was equal to the FEA package used by designers across various engineering problems. Fig.1 represents the mode shapes encountered, Sample 1 especially showing a maximum error between modes of 7%, which occurred at mode 4. This error is somewhat expected as for all initial tests the accelerometer was mounted centrally, and thus from the mode shapes there is little displacement of the sample in this position, therefore the accelerometer has not detected the mode of vibration. However, after repositioning the accelerometer towards the edge of the sample where the displacement is encountered, the mode is detected and comparable to the FEA analysis.

	Sample 1			Sample 2
Mode	Experiment 1 (Hz)	FEA (Hz)	Error (%)	Experiment 1 (Hz)
1	17	16.9	0.295	10
2	45	44.9	0.111	19
3	89.5	99.8	5.441	n/a
4	110.5	129	7.724	n/a
5	151.5	150	0.498	n/a

Fig 1

A similar correspondence in results is found when comparing Sample 3 with the FEA mode shapes with those from the experiment, with all modes being within 5.1% of each other, again representing the accuracy from both approaches. The absence of mode 3 (Fig 2) from the experimental values is due to the mode shape and that the displacement occurs at the extreme edges of the sample, and therefore making it difficult to obtain. However the excellent comparability of the mode shapes bodes well for the investigation of the damping increase from the viscoelastic layer (VL).

	Sample 3			Sample 4
Mode	Experiment 1 (Hz)	FEA (Hz)	Error (%)	Experiment 1 (Hz)
1	15	16.6	5.063	10.25
2	99.5	103	1.728	n/a
3	n/a	198	n/a	n/a
4	285	290	0.870	n/a

Fig. 2

Modeling of Samples 2 and 4 using FEA software proved somewhat problematic and time costly and thus were discarded from the study. After initially thinking the boundary conditions of the models were to fault, as the model is made from three parts it was thought that the method of bonding was the problematic factor. But when modeling an assembly of two parts of steel together making up the same geometry the resultant mode shapes were almost identical. Hence the VL is the source of the problem. Due to its very low modulus of elasticity (5000Pa) it was concluded that the software was recognising the VL as liquid, as the VL is being displaced out the sides of the sample through shear, which is theoretically true but obviously not to these proportions. The study from this point was pure experimentally based. When experimentally tested both samples produced highly damped resonance when impacted represented by the response sideband width (Fig.7-10) with Sample 2 producing two modes and Sample 4 only producing one mode of natural frequency, both of which were lower than the corresponding modes of the undamped samples as could be predicted.

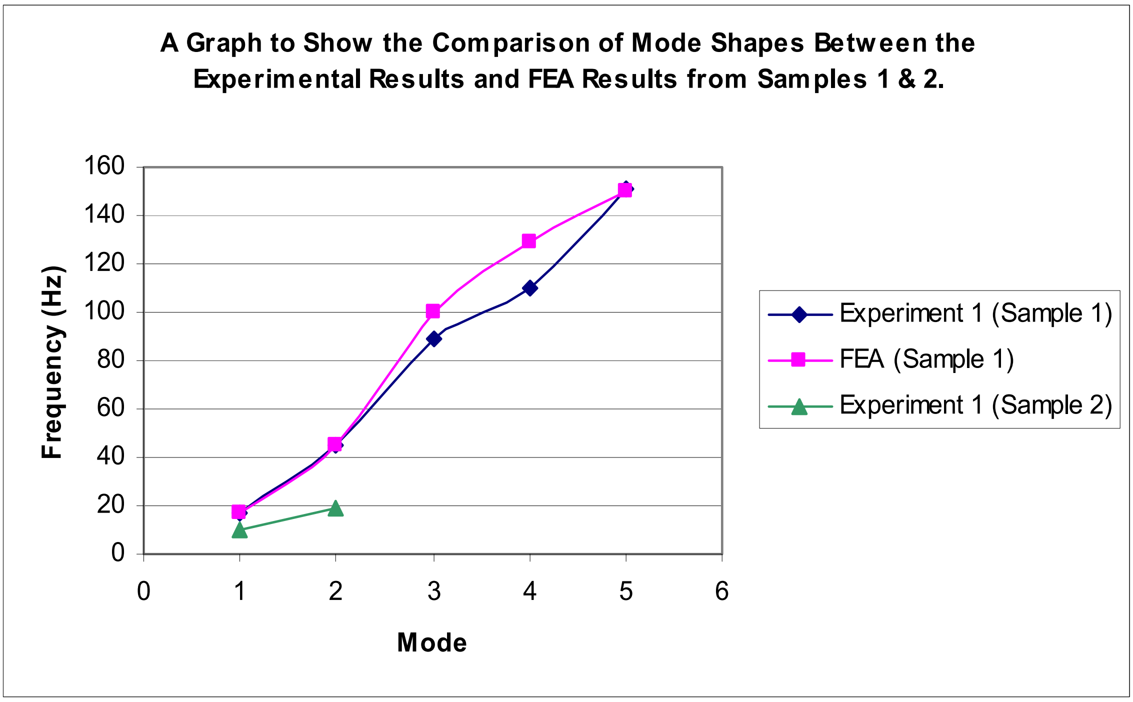

Fig. 3

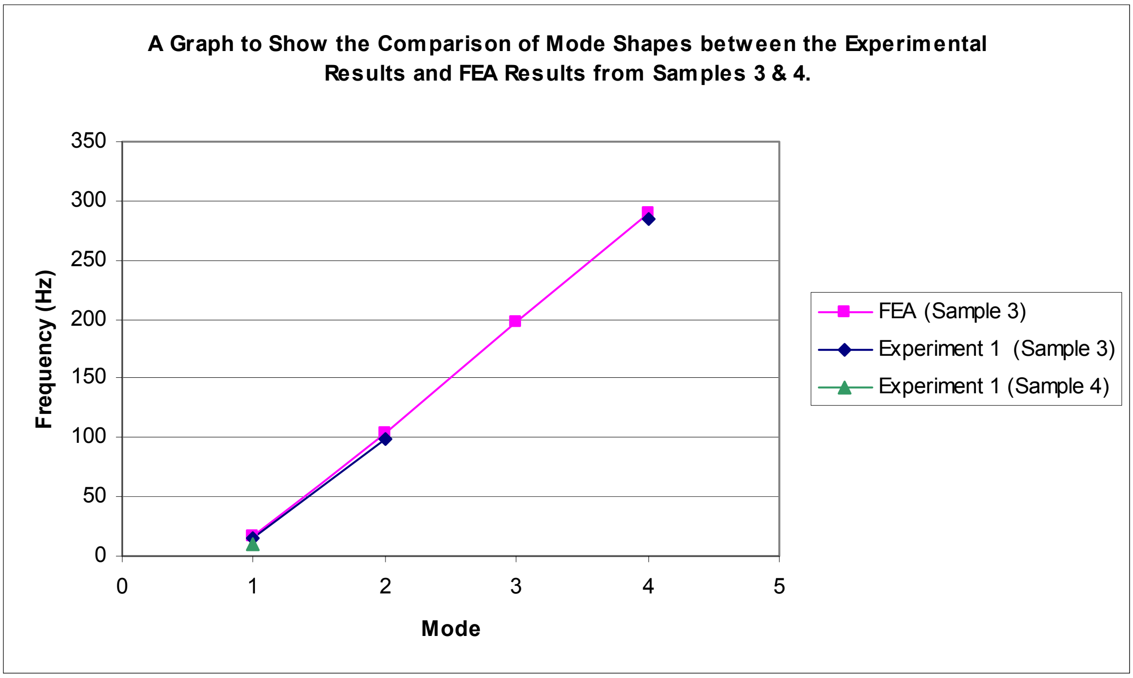

Fig. 4

Damping ratio obtained from damping test (Test 1)

Two approaches were utilised when finding the damping ratio of the samples, Method of Sharpness and Logarithmic Decrement. In terms of Sample 1, 40% error is seen between the methods. It must be noted that the Logarithmic Decrement approach is less accurate as its most predominantly used for the study of single degree of freedom systems, and hence does not produce a result as accurate from that obtained from the method of sharpness, and hence the damping ratios from this method were studied further.

Sample 3's damping ratio is less than Sample 1, which is predicted as Sample 3 is less stiff therefore taking a shorter time to settle. With the samples area being the differentiating factor, as Youngs Modulus and sample length are constant.

It is however, the increase in damping ratio between samples that is of most interest. In the case of Samples 1 and 2, the increase in damping from the VL is 54 % (Fig. 5).

NOTE Mode shape 1 is used for analysis

Damping Ratio				
Method of Sharpness			**Logarithmic Decrement**	
Sample 1	Sample 2	% Increase in Damping	Sample 1	Sample 2
0.0693	0.151	54.106	0.03	0.154

Analytical Error between Methods - Method of Sharpness and Logarithmic Decrement (%)

Sample 1: 39.577%

Sample 2: 0.984%

Fig. 5

With the increase in damping ratio being 78% from the VL from Sample 3 to 4 (Fig. 6).

NOTE Mode shape 1 is used for analysis

Damping Ratio				
Method of Sharpness			**Logarithmic Decrement**	
Sample 3	Sample 4	% Increase in Damping	Sample 3	Sample 4
0.03	0.14	78.571	0.035	0.148

Analytical Error between Methods - Method of Sharpness and Logarithmic Decrement (%)

Sample 3: 7.692%
Sample 4: 3.5%

Fig. 6

In both cases this is a significant increase in damping ratio, especially when considering the reduction in settling time, the lack of overshoot apparent from the impact and the frequency responses sideband width (Fig. 7-10). The following shows the resonant frequencies for the different samples:

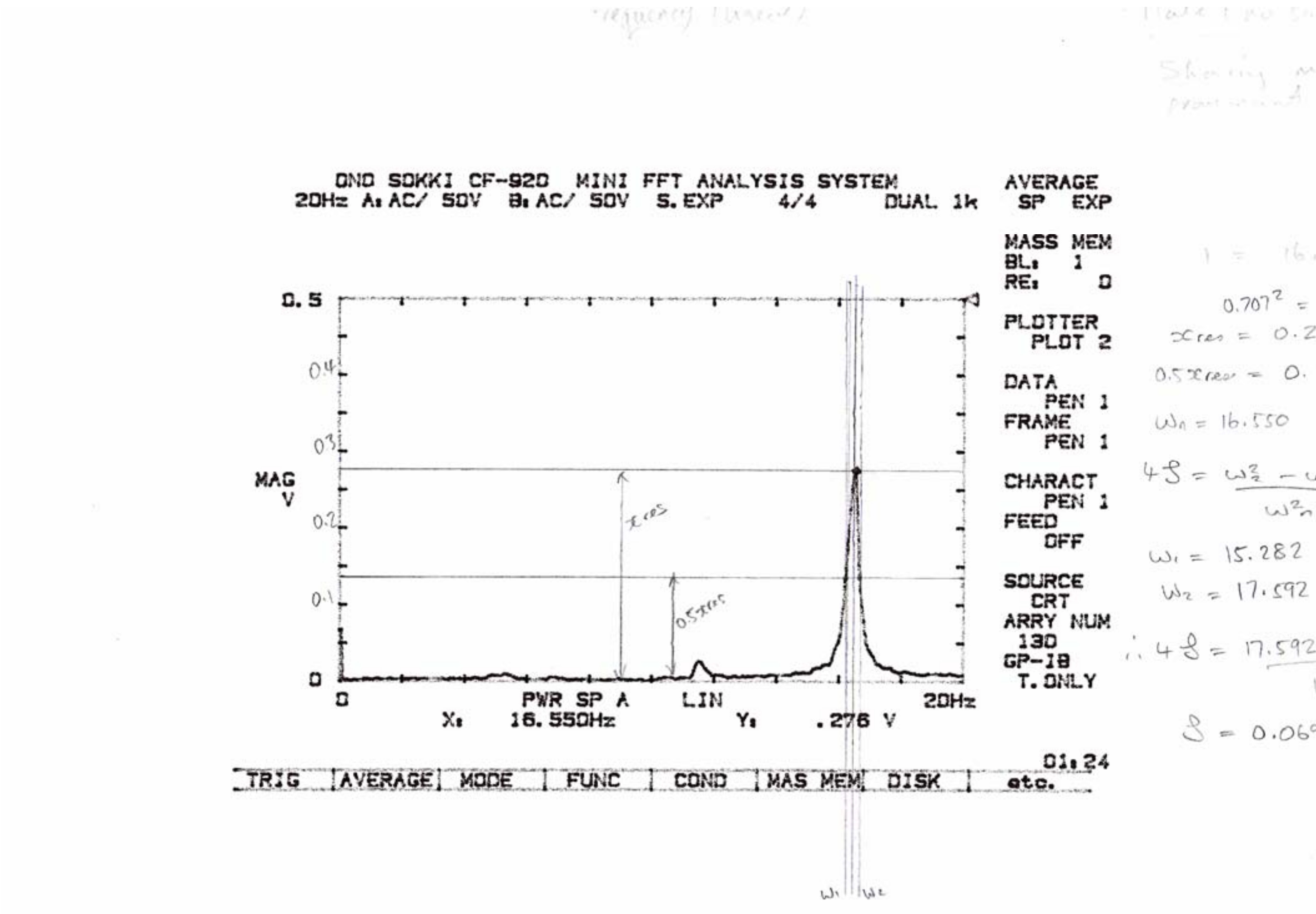

Fig.7 (Sample 1)

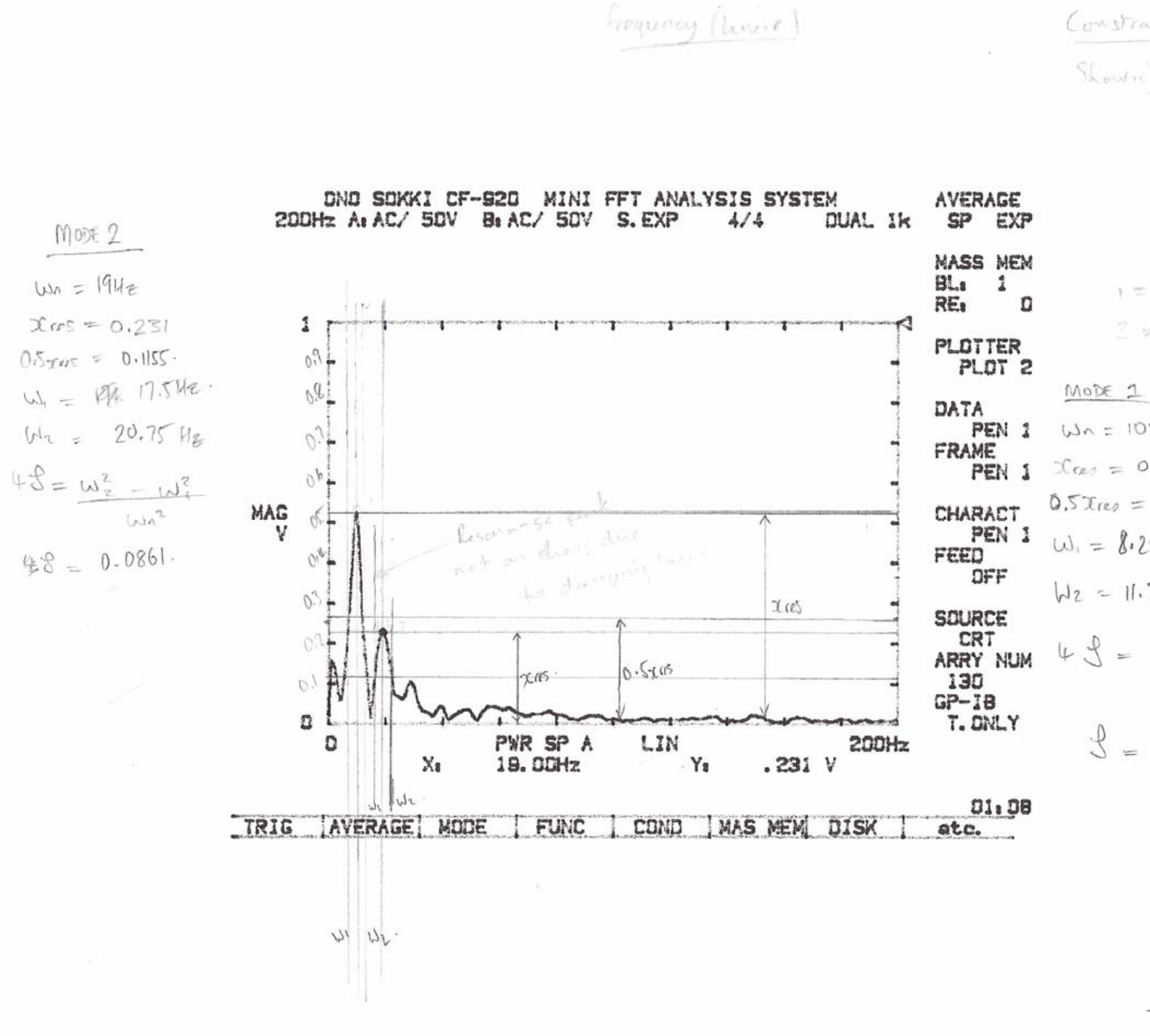

Fig.8 (Sample 2)

Sideband width is less apparent below (Sample 3) as the FFT Analyser was used to zoom into the mode shape to gain a more accurate result.

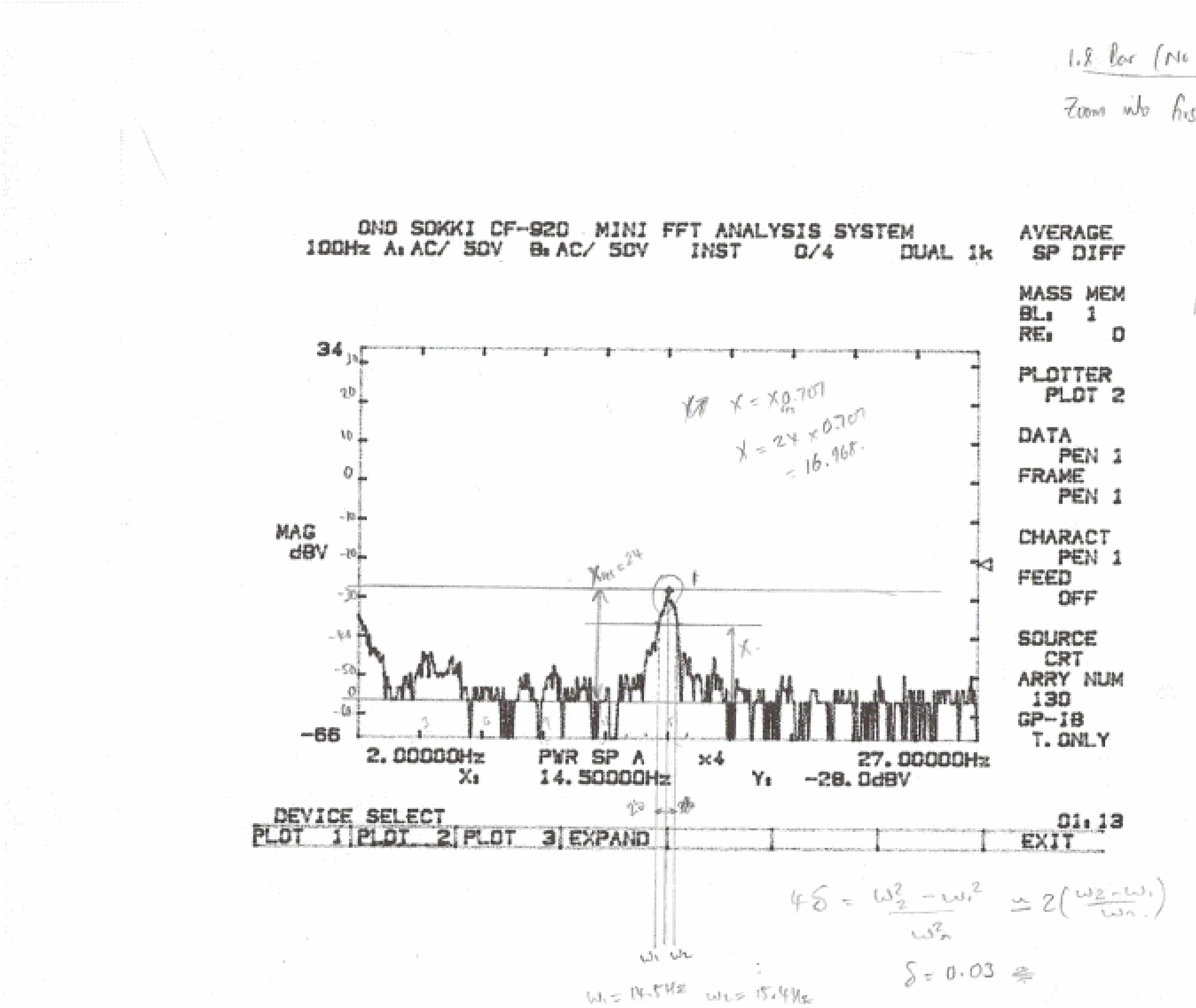

Fig. 9 (Sample 3)

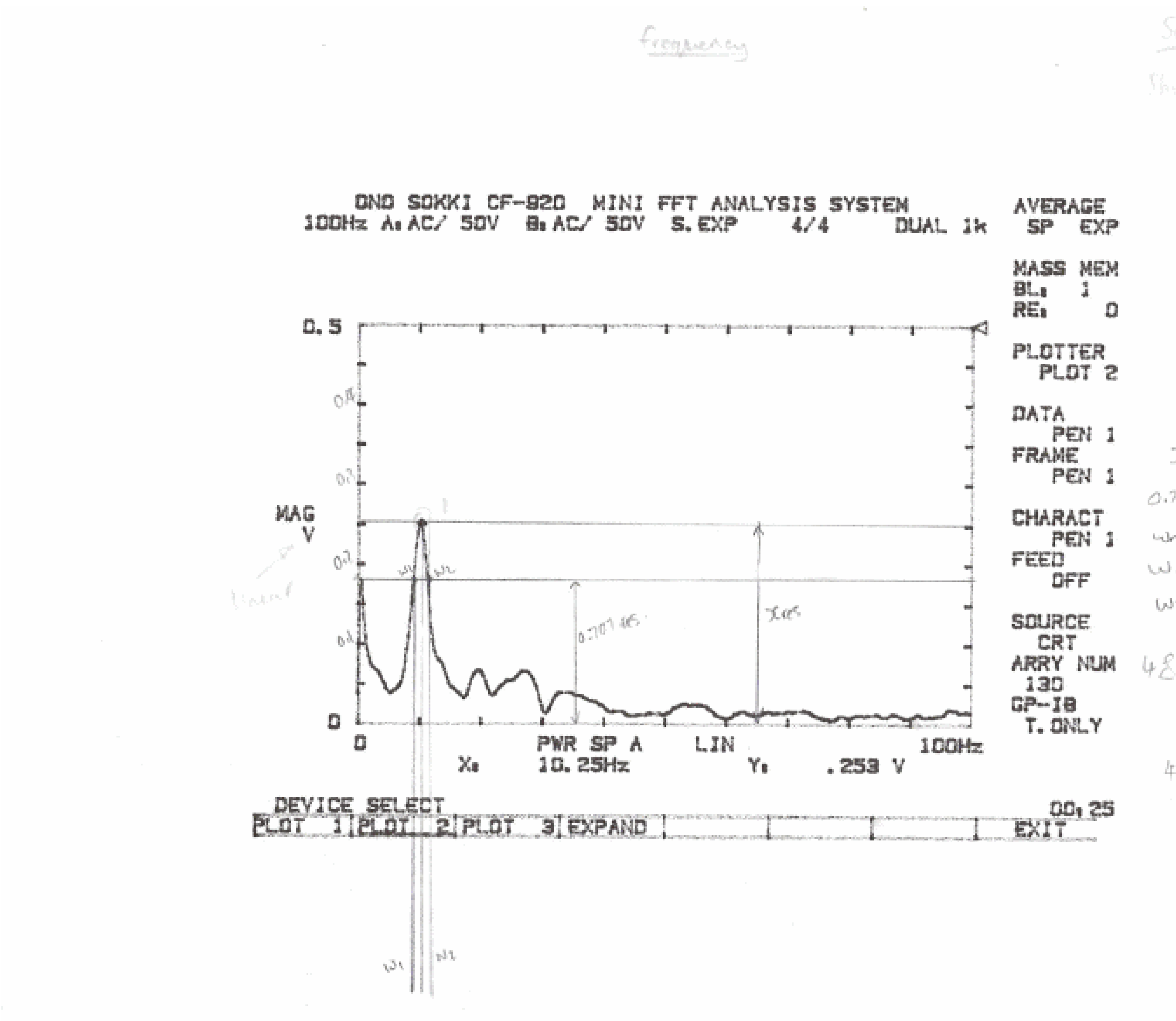

Fig.10 (Sample 4)

Proving the extra energy dissipation from VL is incredibly evident in both cases. A result shown from Fig.11 shows an interesting aspect in the VL performance, with regards to the mass of the samples. Undamped Samples 1 and 3 that possess identical ratio in mass to the damped Samples 2 and 4, and yet the increase in damping from 1 to 3 is 56% and in the case of 2 and 4 an increase of just 7%. Suggesting that, although there is a difference in geometry it has little effect on the performance of the VL's damping characteristic. Or to be more specific the sample thickness is the critical factor in terms of the VL damping capability, and hence the mass is even more essential.

	Mass (Kg)	Damping Ratio	% Increase in Damping
Sample 1	**1.55**	0.0693	**56**

Sample 3	**0.258**	0.03	
Sample 2	**1.4**	0.151	**7.28**
Sample 4	**0.233**	0.14	

Hence mass of the samples has little effect on the performance of the VL in terms of damping.

	Mass (kg)	**% Increase in damping from VL**
Sample 2	**1.4**	**54.106**
Sample 4	**0.233**	**78.571**

Fig.11

From Fig.12 the relationship shows the decay of the VL damping effect as the structure's mass increases and the performance of the VL never changes, but is only affected by the material constraining it and their mass in terms of their thickness. Therefore the change in mass between 2 and 4 has little effect on the VL performance as they are of the same thickness, generating the relation:

$\zeta \alpha m$

Hence the mass at which the VL will no longer have affect is approximately 4kg. An increase in mass with regards to geometry and damping ratio will show that if mass is added by increasing thickness the VL damping will be more affected and reduced. However, if this mass is added through length and width, the level of damping from the VL is less affected but a slow decay remains. Leaving the assumption that, VL damping is most effective at certain geometry and mass. Thus, suggesting that the thickness of the VL must be proportional to thickness of the constraining material to gain maximum efficiency of damping from the VL. An aspect that is not investigated further in this study, but is critical to a structures damping effect.

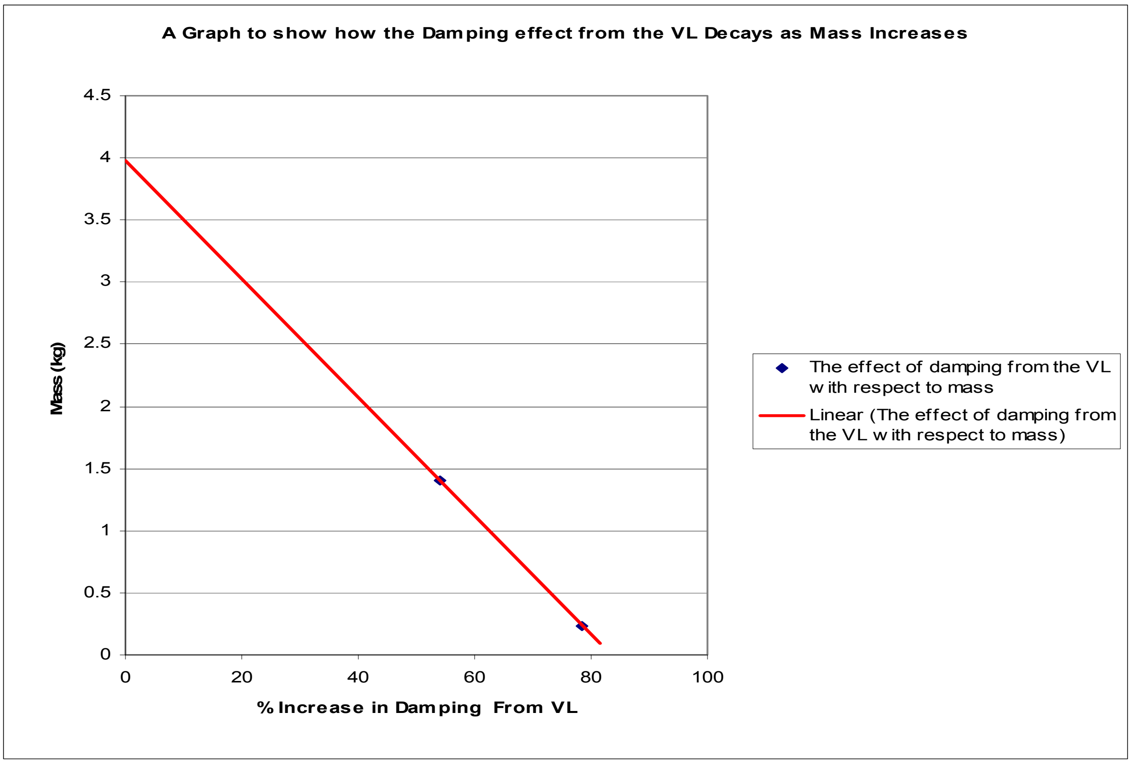

Fig. 12

Therefore in general terms, from the results an accurate prediction can be made; For the greatest damping effect from the VL, the mass of the surrounding structure should be as small as possible, as hence the smaller in mass Samples 3 and 4 a damping ratio increase of 78% is obtained, whereas the larger in mass Samples 1 & 2 a damping ratio of 54% is obtained. Having said that, the VL performance can be assumed constant for different materials, with its performance being totally dependent on the constraining material stiffness and mass. To verify this, further testing could be carried out and would have been involved in this study if time had allowed. From this observation, the question could be asked as to why unconstrained structures do not perform better as they have half the mass and stiffness over constrained structures, yet the advantages the constraining layer has in terms of forcing dissipation through shear, outweigh the unconstrained structures lack of this ability. Also by using the constrained method, the VL is protected from the surrounding environment.

Transmission Loss (Test 2):

The analysis of transmission loss (TL) through Samples 1 and 2 resulted in some interesting findings. Fig.13 and Fig.14 show an accurate representation of the sound pressure level being transmitted through the samples, over a large frequency range, almost identical to that of the human ear. Sample 2 proved to be not as effective as was first predicted, as in many places over the frequency range the TL is actually greater from the undamped Sample 1. Only at frequencies over 3 kHz was the VL more effective at dissipating sound, with the largest difference of 8dB occurring at 6 kHz. It is notably difficult to clearly differentiate between amount of TL between the samples, something that is more important than the maths, to industry and the real world.

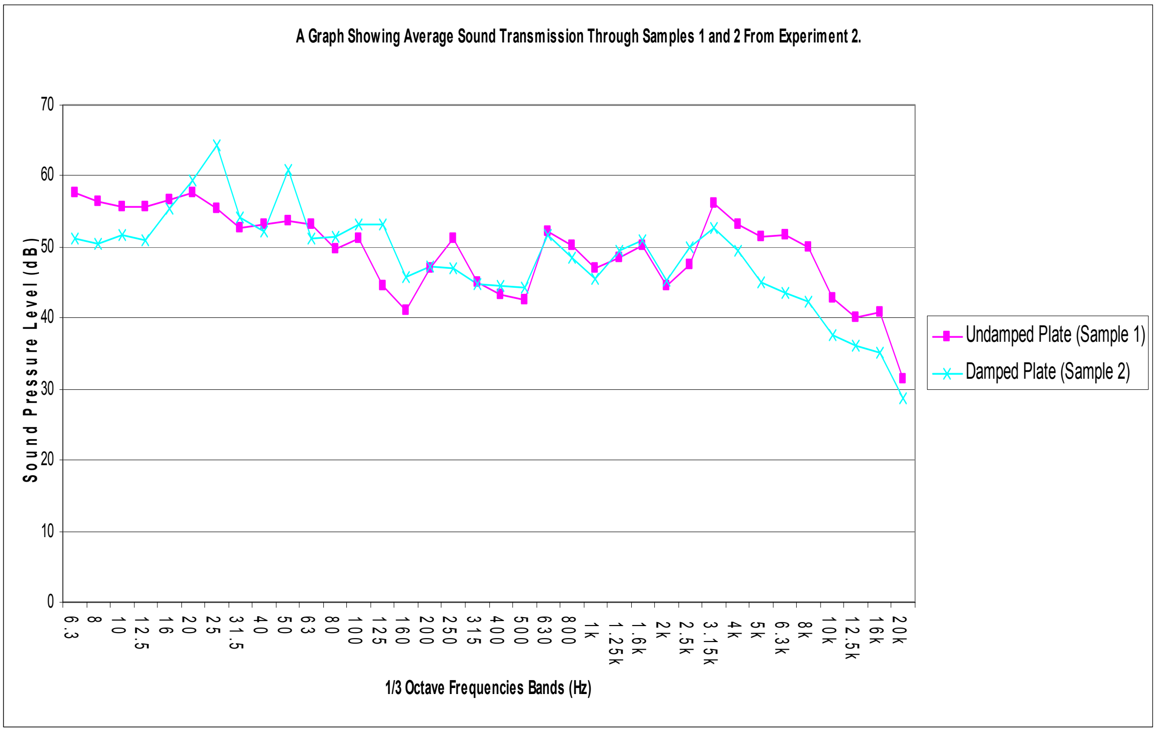

Fig. 13

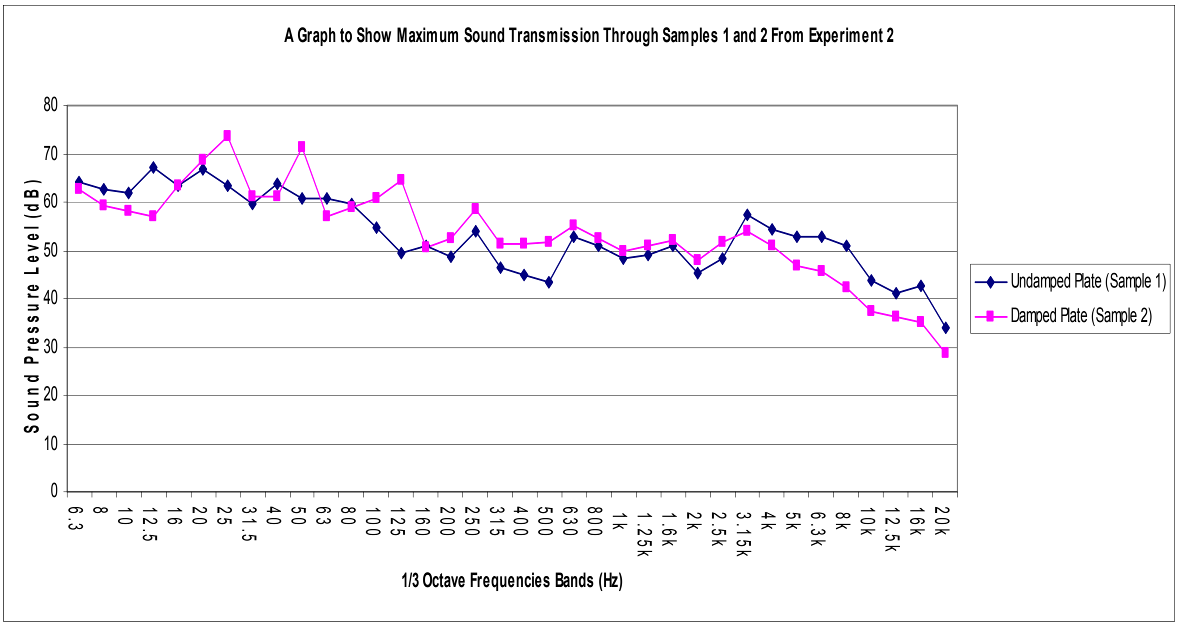

Fig. 14

Under first impression it would be true to think that the VL would increase TL dramatically, as the transmitted white noise should be encouraged to flank laterally along the VL due to its high degree of shear capability, hence less noise would be directly transmitted into the microphone. But only when studying the theory of TL do the similar levels of TL encountered from the samples become more sensible and accurate. The amount, by which TL is affected in terms of structure's level of damping and stiffness, is often negligible. TL is rather more dependent on the structures mass, generally complying with the statement, the greater the structures mass the greater the TL. Thus if the structures mass is doubled, TL increases by approximately 6dB. This would explain the similarity between the data. Sample 1 is 155g larger in mass than Sample 2 so slightly more TL could be expected. However, this would mean that as TL is increased from the VL at larger frequencies of above 3 kHz, then the VL does have a small effect; especially considering Sample 2 also has a smaller mass. Therefore to presume the VL does not have an effect on TL is somewhat untrue, as if Sample 2 was increased in mass by 155g; the amount of TL could only increase. To be more perceptible to the human ear, it's probably not beneficial economically to have a VL if its job is purely to increase TL, as it does not fulfill this role effectively enough.

Another aspect to be considered from the TL experiment is the notable peaks from Sample 2, which can be seen at 25Hz and 50Hz on Fig.13 and Fig.14, suggesting the white noise is causing the sample to resonate. Experiment 4 was carried out to conclude whether any resonance occurred at these frequencies from Sample 2 when positioned on the speaker and impacted. The response encountered shows a small but clear resonance is shown occurring at 23Hz, hence corresponding with the peaks from the TL experiment and complimenting the accuracy of the data. It is unusual that resonance should occur within the sample containing the VL, and especially with no resonance occurring within the undamped Sample 1. Therefore, the resonance must be a knock on effect from the VL and more specifically from the amount of sound energy being dissipated laterally through the VL, causing vibrations over a larger area of the sample, thus causing it to resonate, and as less flanking occurs through Sample 1 hence there is a more direct path of noise transmission, this would explain the slightly larger transmission of noise detected by the microphone. So taking this point into consideration, it is difficult to justify using a VL for transmission loss purposes, as it does offer a small increase in TL, yet this is not great enough to overcome possible problems of resonance. It is felt that TL would be increased from the VL if it is subjected to louder noise, as it would mean that the structure or in this case the samples, would have more vibration to reduce and therefore more reduction in noise occurs. However it can be recognised that even the undamped plate does still contribute significantly to TL when compared to the sound pressure level of the white noise alone.

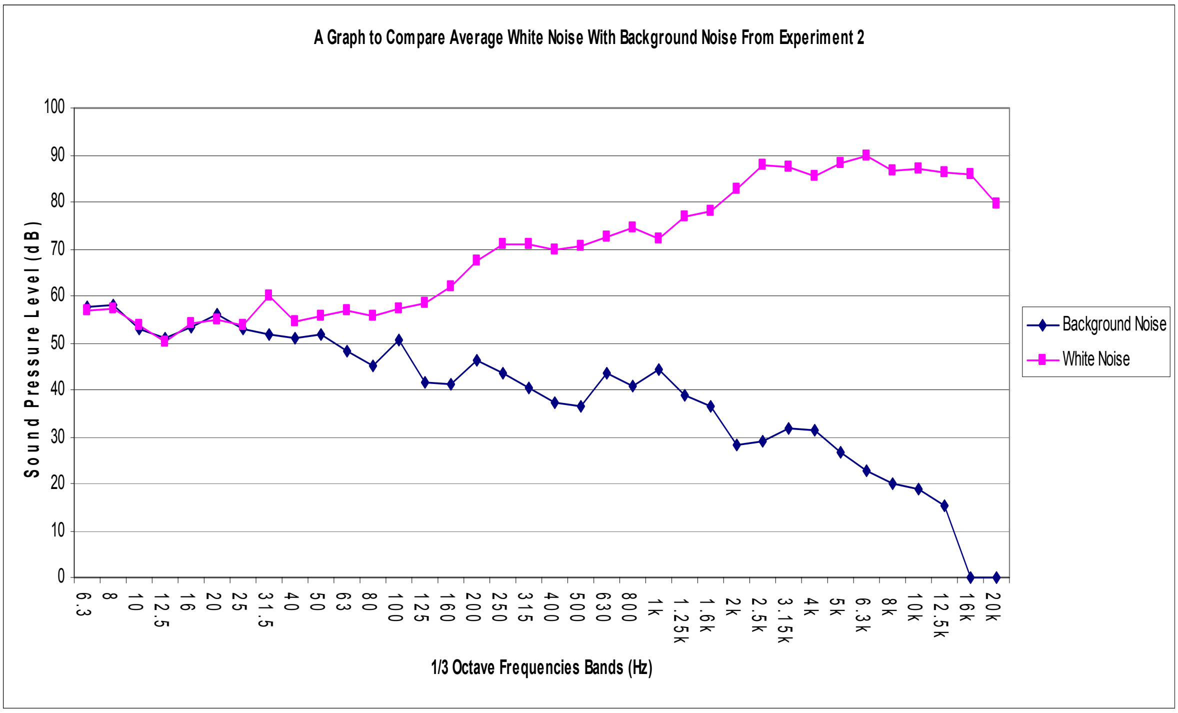

Fig. 15

Impact Test (Test 3)

Having said that, this finding was totally reversed when studying the results obtained from the impact test. Fig.16 and Fig.17 show reductions from the VL of over 20dB from frequencies of 400Hz up to 20 kHz. What is more impressive is the VL performance does not decay to a large extent when the impact force increases. Hence the mass of the ball bearing is 5g with the greatest reduction in noise radiation of 31.5% (23dB) at 630Hz, and the mass of the ceramic ball is 118g, therefore a superior impact force is encountered with the greatest reduction of noise radiation of 22.83% (21dB) at 5 kHz. Thus the impact force from the ceramic ball is almost 24 times greater than the impact force of the ball bearing, but the performance of the VL is reduced by only 8.67%. Again showing the VL efficiency is largely unaffected by in this case the impact of the force. To the human ear this level of noise radiation reduction provided by the VL can be recognised as being four times quieter.

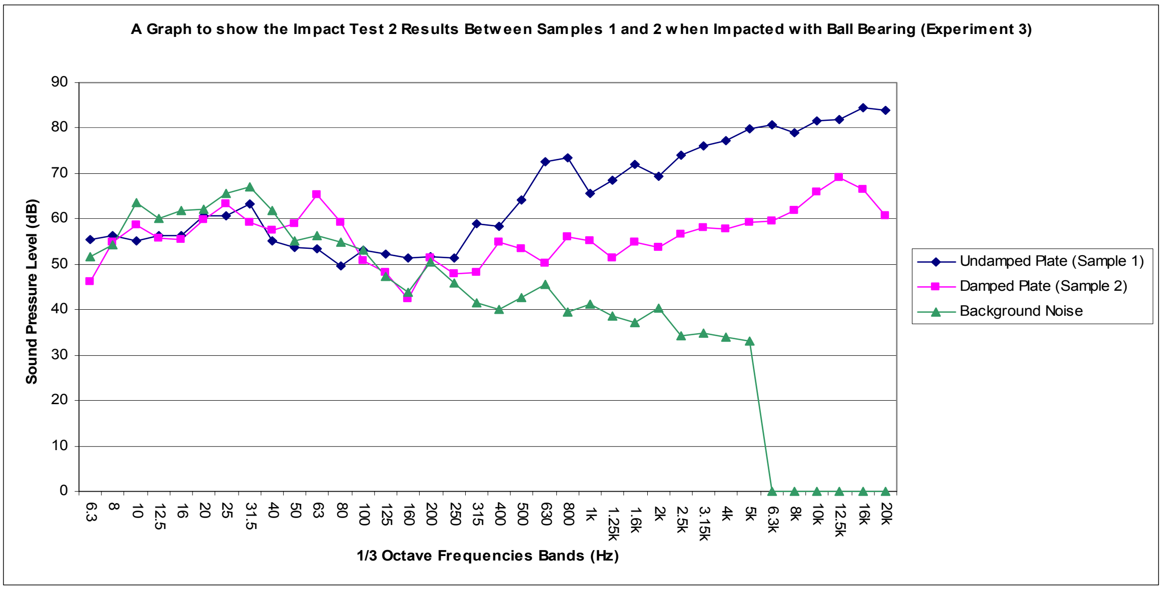

Fig. 16

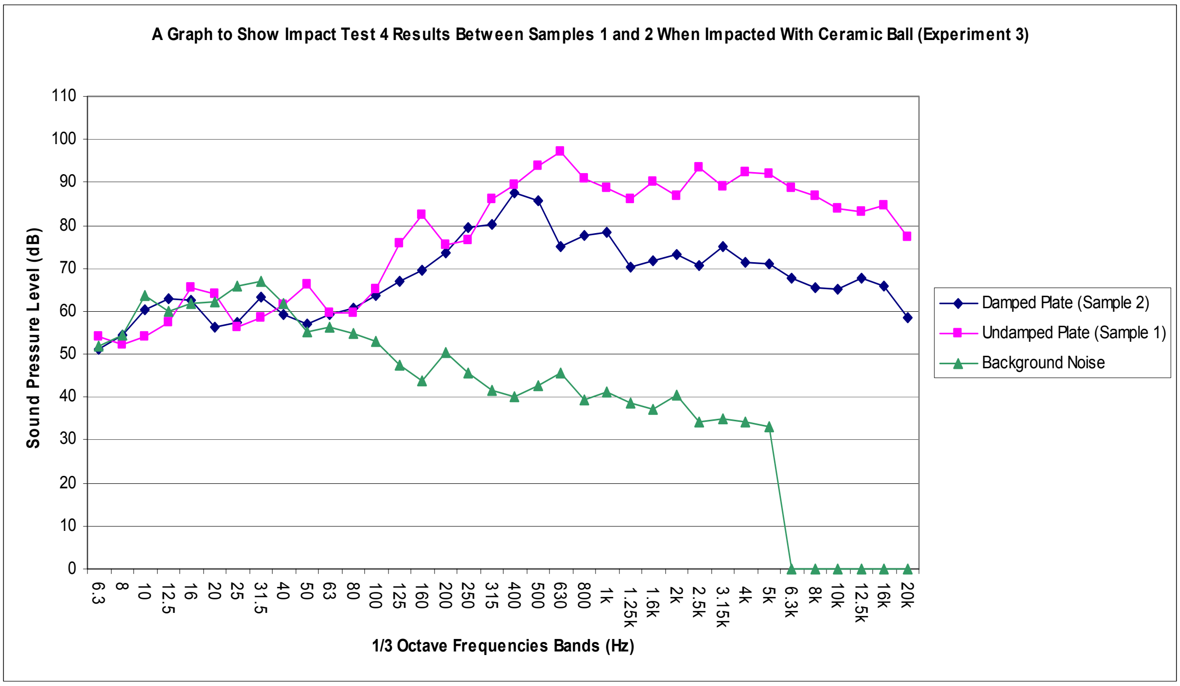

Fig. 17

The source of sound is the vibrations of the samples when impacted, due to the disturbing of the air particles surrounding the source, which is processed within the microphone Therefore the "killing" of noise from the VL is directly related to the large increase in damping encountered. Hence if the vibrations are heavily damped so that energy is dissipated quicker and more effectively therefore their amplitude is made smaller, then the fewer particles are disturbed and less sound is radiated from the source.

Additional Impact Damping Test (Test 5):

The VL as previously discussed, increases damping levels admirably, or more specifically the amplitude of vibration is reduced. This point is further backed up by the findings obtained in the additional impact damping test results shown in Fig.18 where it can be seen that there is a reduction in resonant amplitude of 97.8% from the accelerometer. Therefore vibration oscillation size is reduced dramatically due the constrained VL's ability to dissipate impact energy through shear, resulting in much less sound radiated from the sample.

	Ball Bearing			Ceramic Ball	
	Sample 1	Sample 2	% Decrease in magnitude	Sample 1	Sample 2
Linear Magnitude (mV)	50	1.1	97.8	n/a	n/a

Fig. 18

From the findings it can be predicted as to which environment the VL effect is most advantageous. It is realised that the combination of the effectiveness of the VL's low modulus of elasticity coupled with the steel or any other material constraining it only encourages even more energy to be displaced by the VL. Firstly, it is clear that the VL would be most beneficial to its user if it is been repeatedly impacted or somehow attached to a constantly vibrating structure.

In terms of damping, fatigue is a very important factor when considering a constantly vibrating structure. It is in this situation where VL damping could be introduced to prolong fatigue life considerably. Such a structure could be pipe work carrying fluid that produces constant vibration from the Eddies in the fluids flow. If vibration is reduced it puts less stress on the pipes circumference and the brackets mounting it reducing the chance of fatigue and failure.

With regards to noise reduction, it appears that the VL performs best when attenuating the effect of high impact force and the noise radiated. Used in the right areas the viscoelasticity could be employed to great effect especially in industry, where noise levels are very strict. Within industry, viscoelasticity could be used on impact machines, such as riveters, forming machines and blanking machines, indeed that is under sudden impact. Other applications could be air conditioning ducts, luxury vehicles and domestic appliances. The scope for these benefits is huge and it can be predicted that it is only a matter of time before this technology is more commonly used.

Project Conclusion:

All objects that possess mass and elasticity are capable of vibration and sound. It is the control of these aspects that is vital when designing a component or structure, which will inevitably encounter vibration. The control of sound and vibration, reduces the possibility of fatigue, enables areas of excessive noise to become quieter without decreasing efficiency.

From the results obtained in this investigation, viscoelasticity controls both sound and vibration. What is most evident is the increase in damping provided by the VL and the reduction in noise radiation when impacted. The major points of the study are represented by the 54% and 78% increase in damping from the VL with regards to the plate and bar, and the discovery of how the VL's performance is affected from the constraining materials mass. Also the relationship between this increase in damping and the significant impact noise reduction from the VL is clearly evident. These are areas that may differ depending on the material constraining the VL and the properties they posses as already discussed.

The most intriguing factor concluded from the study, is the possibility of the VL is already significant performance benefits in terms of damping and sound control, being further enhanced by a different constraining material than steel. Something that could be predicted as a result of the study, but would need further testing to support.

When thinking in terms of a working environment, it is difficult to understand why viscoelastic technology has not been developed. Some disadvantages may include, the scope to which it can be applied, for example the effect of the VL is restricted by the mass of the constraining material or to be more specific their thickness and how it could be applied to a structure. Another reason could be the difficulty of analysing the VL using FEA techniques, something that is commonly found in modern day design suites. Or when considering noise reduction, especially in industry, organisations might ask the question "why invest in expensive noise reducing technology when all employees could wear earplugs?"

However these arguments can be negated by using viscoelasticity in the right areas. Due to the small thickness needed for the VL to be most effective, it could be used in many areas, especially when fitted directly to a structure and when simply constraining, on pipe work for instance, thereby not compromising the design of the structure, as viscoelasticity could be applied at a later date.

To a customer something that is quieter and will have a longer product life is an incredible incentive. Also to a designer, the use of VL's can prolong an objects shelf life without the need for over engineering to reduce the chance of fatigue and avoid resonant frequencies. Other advantages of using VL's are that the most reduction in impact noise radiation was apparent from 630 Hz to 20 kHz, frequencies that are most commonly recognised by human ear. In terms of health and safety, this is an extremely vital asset.

The use of viscoelastic technology on structures that are put under sudden impact repeatedly is arguably where it is most effective, and is evident from this study. To arrive at this conclusion is realistic, as the impact tests from the study show dramatic decrease in noise radiation, amplitude of vibration and settling time. Similar benefits from any other form of damping are unheard of.