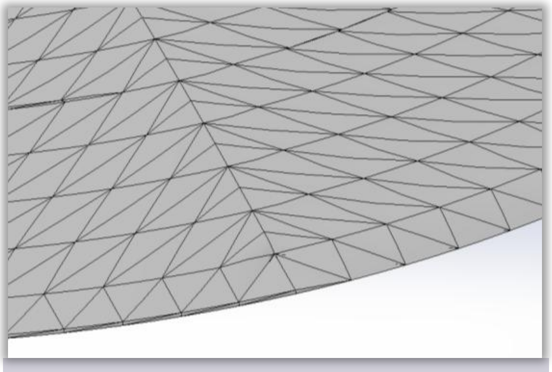
Results of Analysis

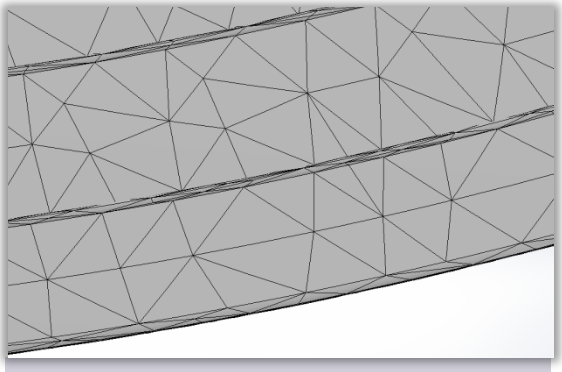
1. The Model & Mesh

The original model used in this experiment is based off of a 14-inch Meinl Crash cymbal - most closely resembling the 'Byzance Traditional Thin Crash' (Meinl, Meinl Cymbal Catalogue - Inspire, 2012), as presented in the proposal.

The original, standard, mesh was unreliable due to the mesh effectively splitting the circle into segments and drawing a straight line along the edge of each segment (see close up to the right - labelled 'standard mesh'). This was unreliable because it caused the frequency mode to be unevenly distributed along these parts and as a result made the cymbal oscillate inaccurately. To combat this problem the standard mesh was replaced with a curvature-based mesh - which took into account the entire curve of the cymbal rather than splitting it up into segments - distributing the mesh almost randomly (see close up to the right - labelled 'curvature mesh'). Upon doing this results appeared to show significantly less bias towards any areas. No specific mesh convergences or divergences were applied because all parts of the model were equally important. This is because the model, as a whole, is being analysed - rather than just a small part of it.



Standard Mesh

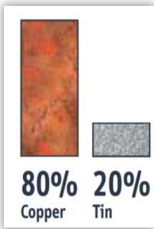


Curvature Mesh

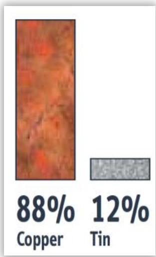
2. Material Comparison

To determine the effect the material had on the frequency of the model five classic alloys in cymbal manufacture (based on the company ‘Meinl’) were chosen and tested using the simulation package in ‘Solidworks’.

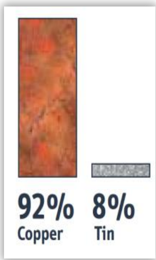
The five alloys chosen are as follows:



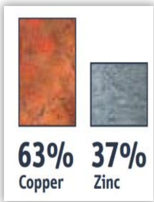
B20



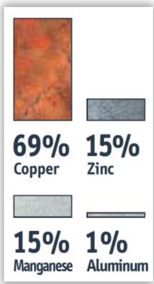
B12



B8



MS63

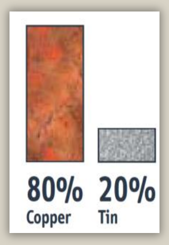


FX9

2.1 Explanation of Materials

Why have different materials?

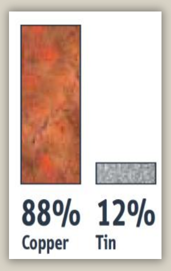
The following aims to define a clear difference between each material with relation to properties, manufacture and musically relevant features. *(Meinl, 2004, Meinl Cymbal Catalogue) (Ekserdjian et al., 2012, Bronze) (Smith, 1981, Structures and Properties of Engineering Alloys) (CES Edupack).*



B20 Alloy

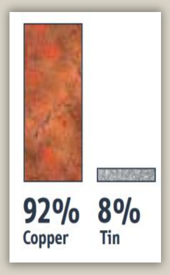
B20 bronze is the most commonly used material in cymbal manufacture. There are several reasons for this; the most important of which (to the company) is the manufacture costs. “B20 bronze has the highest contingent of tin which makes it very soft and flexible”. This, in turn, makes the cymbal much easier to manufacture; making it cheaper to cast, mould and lathe.

In addition to this, cymbals made of this material present a very ‘smooth’ sound when struck, which is very flexible with regards to genre and style – making it a much more logical purchase for general drummers.



B12 Alloy

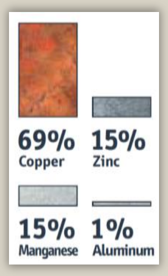
B12 bronze has slightly less tin than B20 so, as a result, is harder and more expensive to manufacture – but it does have significant enough property differences for this to be worth it. The lack of tin makes the material stronger and therefore more durable. This is the typical composition for Bronze alloys. Meinl explains: "They have the powerful sounding characteristics the B8 cymbals are famous for, yet they also a warm and dark overall tone" - much like the B20, so the B12 is a perfect bridge between the two.



B8 Alloy

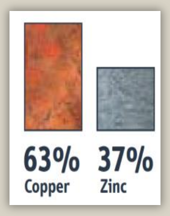
B8 has the lowest percentage of tin and is therefore the strongest of the three bronze alloys. Although this makes this much more difficult to manufacture, it does make the cymbal considerably more durable and easily resists hard playing – so is the ideal cymbal for live performances where a firm play-style is often used.

Cymbals made of B8 generally have a much more lively sound than other cymbals and have a tendency to cut through loud volumes.



FX9 Alloy

FX9 alloy is a much more modern cymbal alloy that has only recently been adopted. It has a very lively sound and is very durable, so will last a long time. It's often part of slightly more expensive cymbal ranges to reflect this. Meinl says that "Cymbals made from FX9 alloy offer new, fresh and lively sounds with a unique and distinctive timbre". It is used for a very clean and crisp music and produces a very sharp sound that doesn't ring on for too long.



MS63 Alloy

MS63 brass is used to produce much cheaper ranges of cymbals - aimed mostly at students. It's sound quality is much lower than other cymbals, but, according to Meinl, has "positive sound characteristics" and "it offers the best possible sound qualities at an affordable price". Despite being quite cheap, it's reasonably durable, and should be able to withstand a lot of battering.

2.2 Material Statistics

The material properties required to complete the frequency anaylsis' are unavailable as alloy-specific properties (Young's Modulus, etc). So in order to get the most accurate material statstics possible to input into the simulation package in Solidworks, the material counterparts in the alloys were extracted using the software 'CES Edupack' and averaged using the alloy compositions (the percentages above) provided by 'Meinl'. Although this method may not be directly accurate to real-life situations because it doesn't directly take into account the chemical properties of the alloy, it does give a reasonable insight into how the change in material effects the frequency – which is the crucial part of these tests.

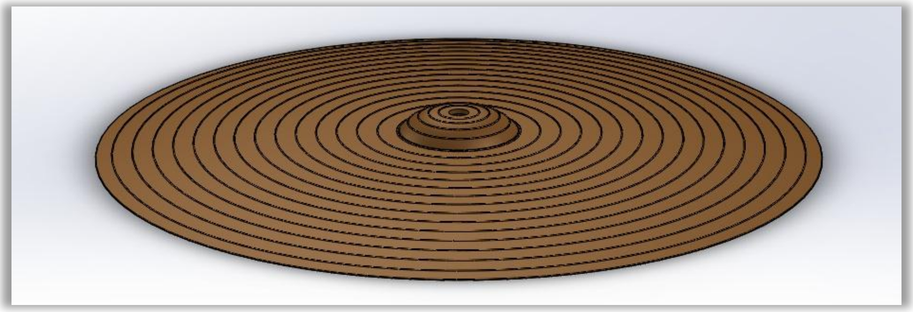
Below is an example of the method used to merge the statstics in the form of a table that displays all the relevent information required for the tests and more.

Property (B20 Alloy)	Unit	Minimum	Maximum	Average
Density	GPa	8600	8614	8607
Price	GBP/kg	1.7108	3.2806	2.4957
Young's Modulus	kg/m³	97.8	127.4	112.6
Poisson's Ratio	-	0.337	0.347	0.342
Tensile Strength	MPa	82.2	323.6	202.9
Elastic Limit	MPa	25.4	283	154.2
Shear Stress	MPa	38.8	45.2	42

(A full table, including all alloys, can be found in the appendicies).

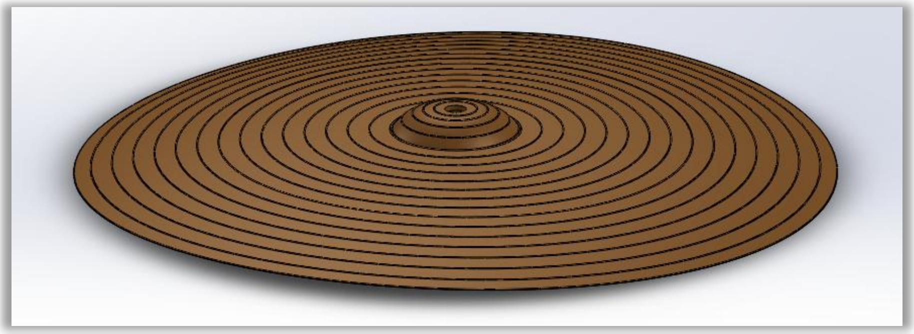
3. Model Sensitivity to key variables & a brief insight into how the deformation of a cymbal effects the frequency

To get an idea of the sensitivity of the model to key variables, some additional models were also set up to mimic the effects of wear such as bending or twisting. These will be used to gauge the accuracy of the tests to real-life conditions; ie. in real life the cymbal would not be perfect, and would be subject to wear such as bending over longer periods of time. (Pinksterboer, 1992, The Cymbal Book).



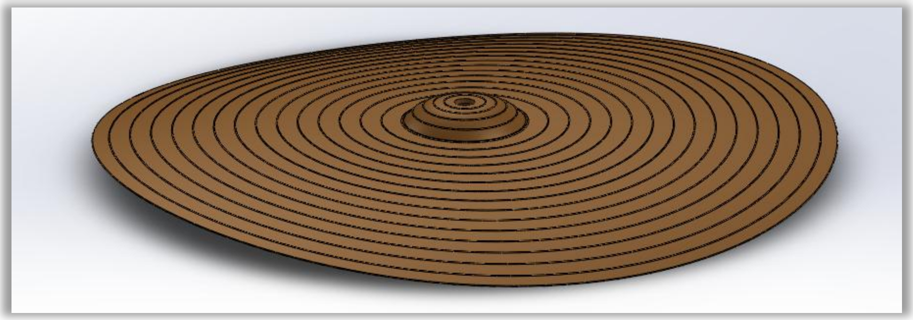
Model 1 - Original

This model represents the perfectly constructed, brand new cymbal with no defects.



Model 2 - Bend

This model has a 10-degree bend deformation in it to represent defects in order to measure sensitivity.



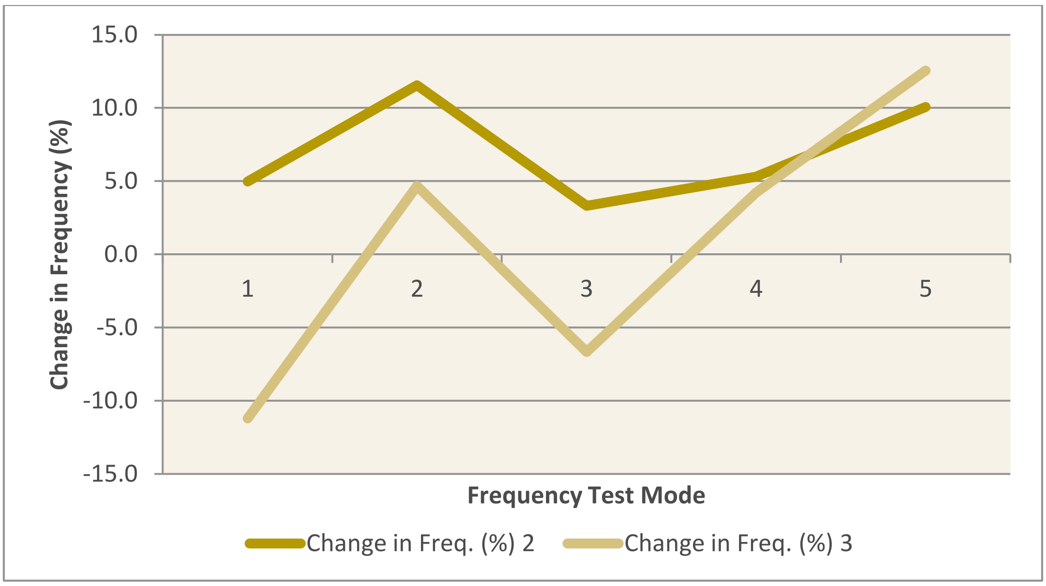
Model 3 - Twist

This model has an alternative deformation in the form of a 10-degree twist, to enhance the reliability of the sensitivity tests.

Model 1, 2 and 3 in the table are the same as described above, as well as 'Change in Freq. (%) 2/3' - the numbers being representitive of the model.

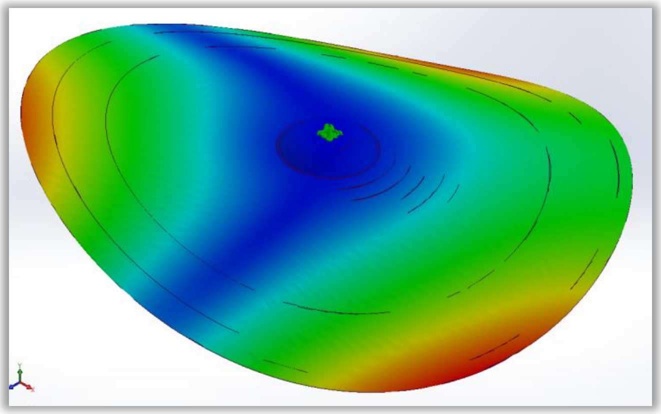
	Tests 1 - 5 - Frequency (Hertz)				
B20 Alloy	1	2	3	4	5
Model 1 (Original)	81.407	82.468	93.491	95.209	193.77
Model 2 (Bend 10)	85.455	91.984	96.598	100.25	213.25
Model 3 (Twist 10)	72.272	86.313	87.262	99.218	218.1
Change in Freq. (%) 2	5.0	11.5	3.3	5.3	10.1
Change in Freq. (%) 3	-11.2	4.7	-6.7	4.2	12.6

Table of results from a frequency analysis test of all three models over fivemodes of frequency - each test represents a seperate mode.



Graph displaying change in frequency, measured as a percentage.

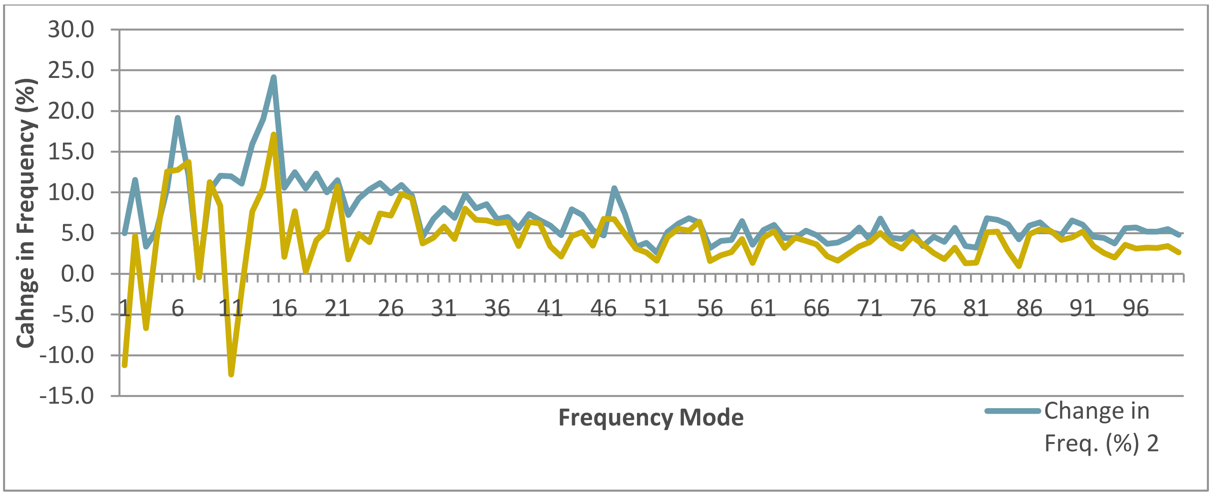
The results demonstrate that the deformation in the model *does* have a significant effect on the frequency of the cymbal. Interestingly, 'Model 3' jumps between increased and decreased frequencies dependant on each test. This is likely to be because of the variance in each test - each being representative of a different frequency mode. So although one oscillation may cause reduced frequency, another may cause it to increase due to the bend deformation in the model being aligned on the same plane as the oscillation - effectively amplifying it. The figure to the right (visualizing the deformation in frequency mode '2' of 'model 3') demonstrates this.



Model 3 - Twist

The deformation shown in the model from the oscillations shows an amplified oscillation due to the original deformation in the model - giving way at the previously bent (or 'twisted') areas as expected.

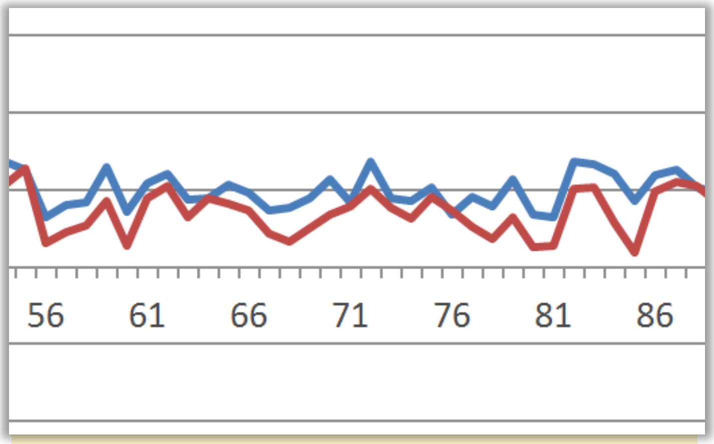
To further this experiment the test was done again to get a more detailed insight into what exactly is happening - this time with 100 separate modes of frequency. The graph below displays this.



Graph displaying change in frequency, measured as a percentage.

The graph matches the hypothesis previously made; with frequencies appearing to converge at around an increase of 4% due to oscillations becoming aligned with the deformation. Decreases in frequency are nullified beyond mode 11, because in order for the change in frequency to be decreased, the oscillations must be mostly perpendicular to the plane of deformation in the model, but as the nnumber of modes increases, the chance of this happening becomes increasingly less likely.

Taking a closer look at the graph reveals that, in most cases, the two variations in deformation - despite being different kinds of deformation - are directly related. The figure to the right shows a portion of the graph zoomed in to get a more detailed view, and demonstrates that the main determining factor is *not* necessarily the *type* of deformation (such as bend or twist), its simply that there *is* a deformation which results in the frequency becoming inconstistent throughout the model. However it can be assumed that the amplitude of the deformation will, in turn, amplify the change in frequency.



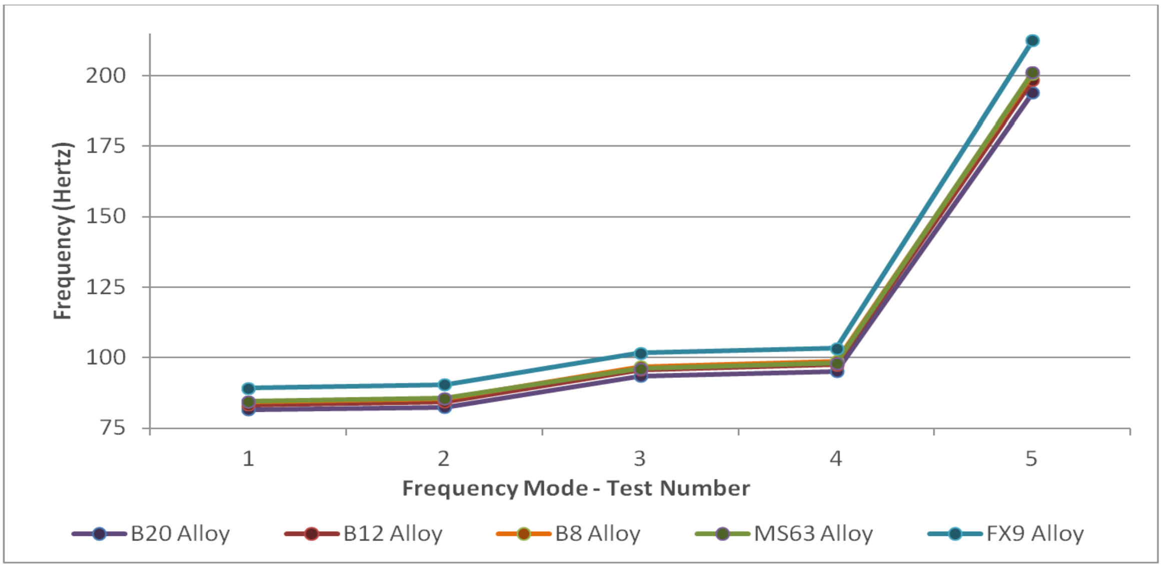
The two graphs produce a similar pattern.

4. Results of Frequency Analysis

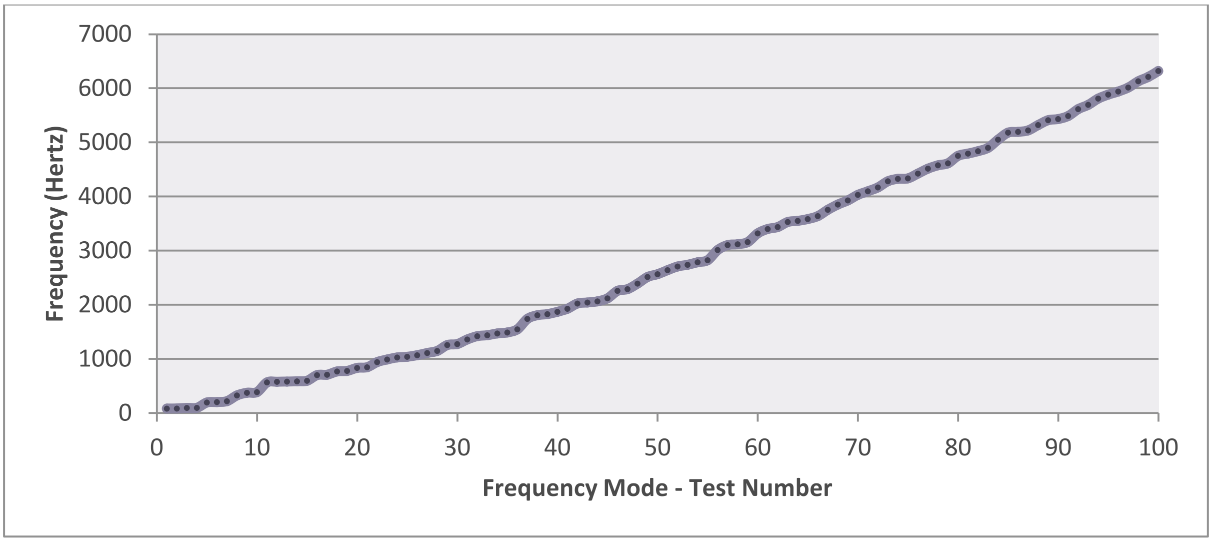
4.1 Material Variation

A full table of results will be included in the appendicies.

The results of the full frequency analysis including all material variation and seperate model variation gave an excellent description of how the material effects the frequency of a cymbal.



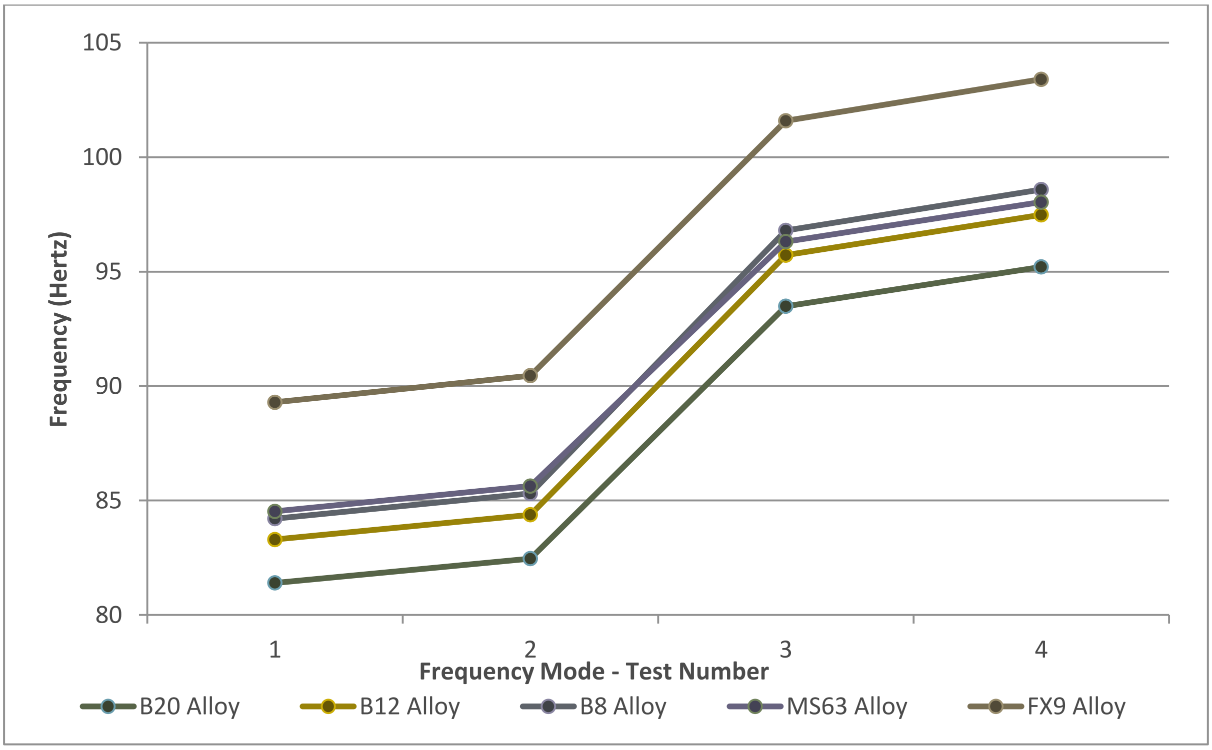
The graph above shows a direct comparison between the five alloys described previously, as the result of a frequency analysis in identical circumstances. It displays a clear difference between the alloys, with the percentage difference remaining fairly consistant throughout. Interestingly, there is a large spike in frequency on the fifth mode of frequency. From the results it can also be noted that the frequency at this point is unusually low for a cymbal (the typical average frequency for a 14-inch crash cymbal averaging around 4000Hz), this is simply because striking a cymbal with a drumstick would result in far more modes of frequency being used (as well as being a bit more random). To demonstrate this, a further test was done on the B20 alloy model - this time with 100 modes of frequency - to see how the results will differ, and to explain the apparent anomoly found on the fifth mode of frequency above.



Graph displaying Frequency Mode against Frequency of Model 1, B20 Alloy

The graph shows a very distinct positive correlation between the mode of frequency and the frequency itself - with the frequency increasing along with the mode (and the average 14-inch crash cymbal frequency - 4000Hz - being reached at around the 70th mode of frequency). In addition to this; the apparent anomoly discovered in the previous results appears to be continuous - with sudden jumps of 60-150 hertz appearing on about every 5 frequency modes on average. This is likely to be the result of a threshold point relating to the mode of frequency and the model itself; when the mode of frequency reaches this threshold it gives way - amplifying the frequency, and appearing as a sudden jump in the results.

To get a closer look at the average change in frequency between each alloy, modes 1 - 4 will be analysed in more detail.



The graph above displays the average change in frequency for each of the modes of frequency and each material - measured as a percentage change. All the results are a direct comparison to the B20 alloy. This is a useful gauge of the effect the material has on the frequency of the cymbal. The results show that FX9 alloy has the biggest variation to B20 Alloy, at an average of 9.16%.

Freq. Mode	B12	B8	MS63	FX9
1	2.32	3.45	3.83	9.68
2	2.32	3.44	3.84	9.69
3	2.39	3.54	3.02	8.66
4	2.39	3.55	2.97	8.60
Average (%)	2.35	3.50	3.41	9.16

4.2 Why is this important?

Although the 2.35 - 9.16% change in frequency may not sound like a huge variation, it's effects on the sound of the cymbal as an instrument are huge. This small change is enough to have a huge impact on the musical properties of the cymbal, as well as how it feels to the drummer to strike. This small change of frequency will effect numerous attributes of the cymbal; such as pitch, loudness, sharpness of sound and even how long the ringing of the cymbal continues on before fading out.

For example; the difference in frequency between the notes B_7 (3951Hz) and C_8 (4186Hz) is just 235Hz, which is only a 5.9% increase (Alten, 2012, p.21)

It's essential, therefore, that the material is chosen to be relevant to the style in which is to be played.

5. Discussion of Results

5.1 Model Limitations

Obviously it's impossible to create a perfect model of a real-life cymbal using Solidworks - that takes into account every possibility, every imperfection and every minor indent that *could* affect the resultant frequency - just like how it's impossible to record perfect frequency results on a real cymbal. Every method has its downside, and although the model was made with every measurable detail considered - it still may not be perfect. *(Image to the right - www.photoree.com - 'Cymbal Circles').*

5.2 Comparison to Expected Results

The results of the tests do reflect what they were expected to with reference to the explanation of cymbal alloys outlined earlier in this paper. Looking in detail at the two alloys at opposite ends of the spectrum gives a good perspective of this:

B20 Alloy

The lowest frequency alloy of the five tested - described by 'Meinl' as sounding "Very dark and musical. They blend in perfectly with the music and have a smooth feel when hit." - which definitely fits the results. The B20 Alloy is the softest out of all the analysed materials and is therefore also likely to be the smoothest when struck.

FX9 Alloy

This time the highest frequency alloy of the five tested - described by 'Meinl' as sounding "Bright" and "Warm" along with "Cymbals made from FX9 alloy offer new, fresh and lively sounds with a unique and distinctive timbre" - fitting the results found, with it appearing as the highest frequency of the group analysed.

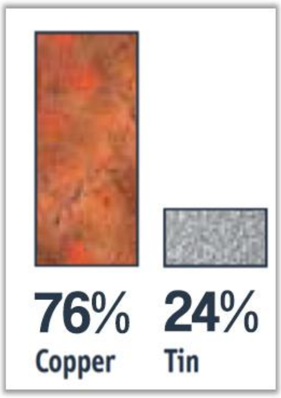
Unfortunately it's not possible make a direct comparison with results of previous papers or books simply because it's never been looked at in this level of detail as a finite element analysis. Musical properties of percussion such a drums and cymbals are almost always measured as a by-ear basis - meaning there is no defined measurement of how these instruments should sound, because cymbals are primarily very traditional pieces of percussion, as are the companies that manufacture them.

6. Designing a Cymbal Alloy

6.1 Determining the alloy composition

To determine the necessary alloy composition key cymbal properties must be chosen to reflect what the cymbal should be like once completed. For this test two alloys are going to be generated; one a very 'dark', 'smooth' cymbal with a low frequency, and one very 'lively', 'powerful' and 'bright' - extreme versions of the B8 and B20 Bronze alloys. So for this test the compositions will simply be tweaked slightly.

6.2 The new alloy compositions



Property	Unit	Minimum	Maximum	Average
B24 Alloy				
Density	GPa	8534.0	8548.8	8541.4
Price	GBP/kg	1.8	3.3	2.6
Youngs Modulus	kg/m³	95.0	123.3	109.1
Poisson's Ratio	-	0.3	0.3	0.3
Tensile Strength	MPa	78.6	308.3	193.5
Elastic Limit	MPa	24.5	269.6	147.0
Shear Stress	MPa	37.6	43.8	40.7
B6 Alloy				
Density	GPa	8831.0	8842.2	8836.6
Price	GBP/kg	1.4	3.1	2.3
Youngs Modulus	kg/m³	107.7	141.8	124.8
Poisson's Ratio	-	0.3	0.3	0.3
Tensile Strength	MPa	94.7	377.1	235.9
Elastic Limit	MPa	28.6	329.9	179.3
Shear Stress	MPa	43.1	50.0	46.6

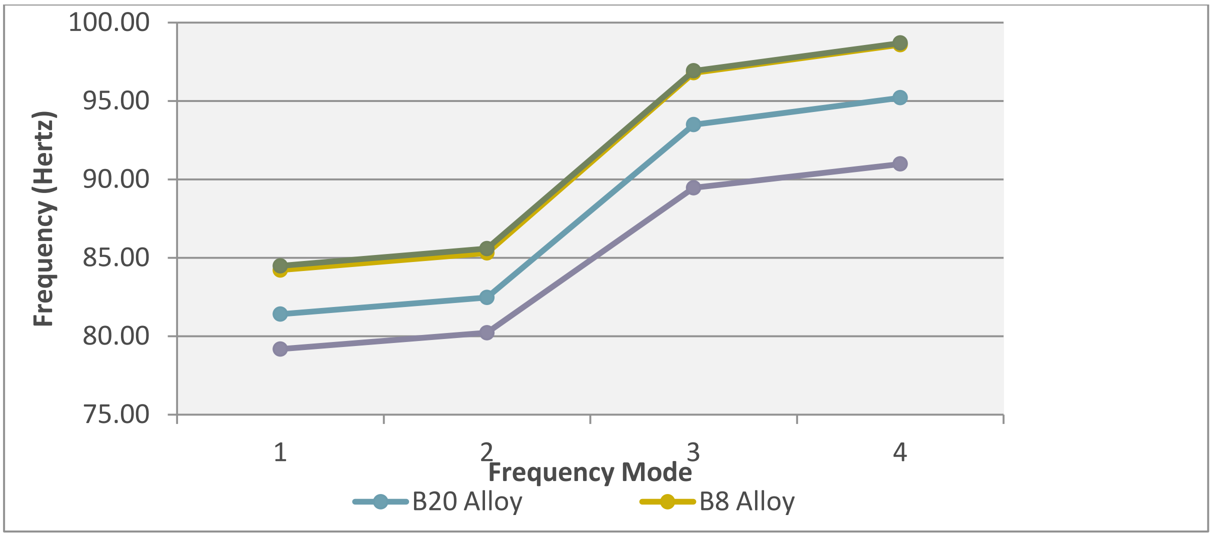
For this test the alloys have been altered to become B24 and B6 - entirely new bronze allows. The compositions were re-calculated using the same method as the alloys. The new properties are listed above and all the necessary properties are imported into Solidworks

Elastic modulus	1.091e+011	N/m^2
Poisson's ratio	0.3	N/A
Shear modulus	40700000	N/m^2
Mass density	8541.4	kg/m^3
Tensile strength	193500000	N/m^2
Compressive Strength in X		N/m^2
Yield Strength		N/m^2
Thermal Expansion Coefficient in X		/K

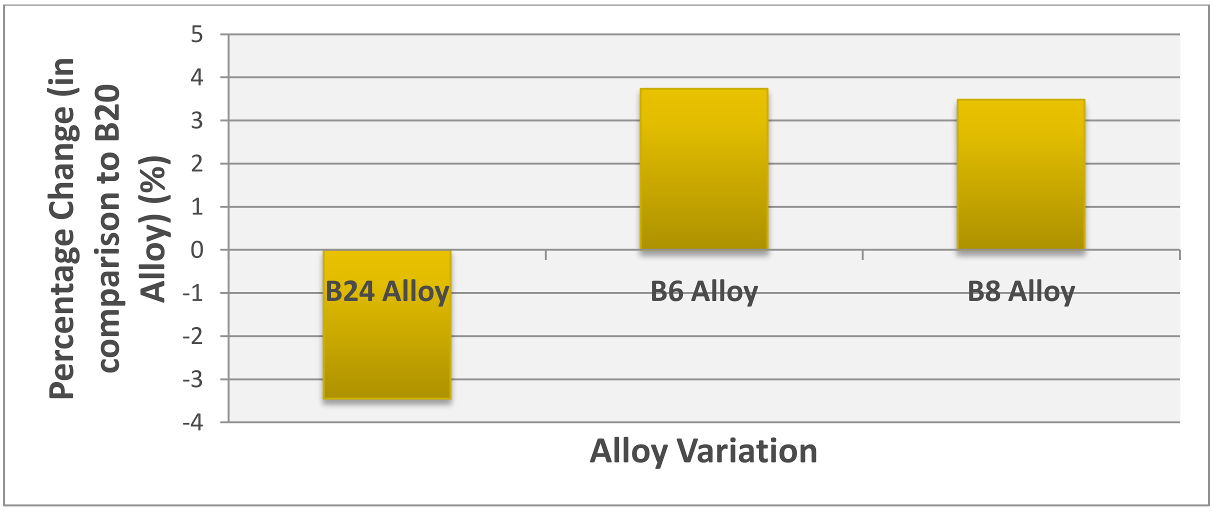
6.3 Results

	Tests 1 - 5 - Frequency (Hertz)					
Alloy	**1**	**2**	**3**	**4**	**5**	
B24 Alloy	79.18	80.22	89.46	90.99	187.93	
B6 Alloy	84.48	85.58	96.92	98.70	201.11	
B20 Alloy	81.41	82.47	93.49	95.21	193.77	
B8 Alloy	84.21	85.31	96.80	98.59	200.43	
	Percentage Change (%) (to B20)					**Average**
B24 Alloy	-2.74	-2.73	-4.31	-4.44	-3.014	-3.44692
B6 Alloy	3.777	3.777	3.672	3.667	3.788	3.736243
B8 Alloy	3.447	3.445	3.542	3.547	3.4371	3.483473

To accurately gauge the variance in result B24 and B6 were compared directly to their nearest similar alloys - B20 and B8. The results displayed a success in predicting cymbal properties based on the composition of an alloy.



To get a more precise view of the variance of the new alloys the results below are displayed as an average percentage change in relation to the current B20 alloy.



7. Conclusions

From the results found it can be concluded that the material does have a distinct effect on the sound of the cymbal, giving it various attributes depending on the alloy in question. Based on the results, the properties of each material gathered from CES EduPack and the material explanations Meinl provide; it's possible to draw various conclusions on the effects of the composition of each alloy, what each sub-material offers the alloy and how it effects the resultant cymbal:

Copper

The base of all the alloys - copper is always present - not only as part of, but the majority of, all the alloy compositions. Copper is a cheap, soft, material that can be easily shaped and has good musical characteristics that mimic traditional cymbal manufacture - the traditional material being a B12 Alloy (typical bronze).

Tin

Present in all Bronze alloys; B20, B12 and B8 - the number referring to the percentage of Tin in the alloy. The presence of tin appears to decrease the frequency of a cymbal, which in turn produces a darker and smoother sound.

Zinc

Appears only in FX9 and MS63 alloys. Zinc is a very cheap material, so is often used for lower-range student cymbals. In MS63 Brass alloy, Zinc plays a large role - taking up 37% of the composition, yet the results from testing tell us that it has very similar attributes to the B8 alloy used.

Manganese

Present only in FX9 - helps to produce a very bright and sharp sound, making FX9 the highest frequency alloy tested. Manganese has a high density and provides a lot of strength to the cymbal.

Aluminium

Only appearing in FX9, not much can be said about Aluminium other than it has a very low density and therefore makes the cymbal slightly softer. Only makes up 1% of the FX9 composition.

8. Reflection

8.1 What have you learnt?

An in-depth understanding of Solidworks simulation and how to apply it to various situations as well as generally becoming much more comfortable using it. Learnt how to compile a paper based on the results of a set of experiments in addition to analysing and evaluating it.

8.2 What would you do differently?

I would have liked to have taken the project in a different direction from the start and focus more on the effects the material composition has on the properties of the resultant cymbal. Although the deformation analysis did provide an excellent and very useful insight into how the oscillations effected the cymbal - which gave me a better understanding of the project as whole - I found that the material analysis was much more useful towards finding a possible method of improving current cymbal alloys (the next paragraph outlines what I would have liked to have done instead).

8.3 What would you do next?

Explore the possibility of designing equations based off of material properties in order to discover a resultant frequency range and reproduce cymbal properties to predict alternatives to cymbal alloys with the aim of improving cymbal production. The stability of the results through the analysis - displayed by fairly predictable graph-patterns - means it's likely to be possible to produce a method of determining resultant sound properties by inputting materials into a equation. This would be an interesting and possibly revolutionary concept for cymbal manufacture because, by re-arranging the equation, it would allow efficient predictions on how to generate specific sounds in the form of particular notes or even other attributes such as how it feels to strike; ie. softness.

Barnee Lloyd

References (including all from Proposal and Full Paper):

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Appendicies

Table of Materials

Property	Unit	Minimum	Maximum	Average
B20 Alloy				
Density	GPa	8600	8614	8607
Price	GBP/kg	1.7108	3.2806	2.4957
Youngs Modulus	kg/m³	97.8	127.4	112.6
Poisson's Ratio	-	0.337	0.347	0.342
Tensile Strength	MPa	82.2	323.6	202.9
Elastic Limit	MPa	25.4	283	154.2
Shear Stress	MPa	38.8	45.2	42
B12 Alloy				
Density	GPa	8732	8744.4	8738.2
Price	GBP/kg	1.54648	3.16836	2.35742
Youngs Modulus	kg/m³	103.48	135.64	119.56
Poisson's Ratio	-	0.3382	0.3482	0.3432
Tensile Strength	MPa	89.32	354.16	221.74
Elastic Limit	MPa	27.24	309.8	168.52
Shear Stress	MPa	41.28	47.92	44.6
B8 Alloy				
Density	GPa	8798	8809.6	8803.8
Price	GBP/kg	1.46432	3.11224	2.28828
Youngs Modulus	kg/m³	106.32	139.76	123.04
Poisson's Ratio	-	0.3388	0.3488	0.3438
Tensile Strength	MPa	92.88	369.44	231.16
Elastic Limit	MPa	28.16	323.2	175.68
Shear Stress	MPa	42.52	49.28	45.9
MS63 Alloy				
Density	GPa	8264	8277.7	8270.85
Price	GBP/kg	1.0595	2.26	1.65975
Youngs Modulus	kg/m³	103.86	132.83	118.345
Poisson's Ratio	-	0.3067	0.3426	0.32465
Tensile Strength	MPa	96.3	326	211.15
Elastic Limit	MPa	46.65	281.92	164.285
Shear Stress	MPa	41.3	49.41	45.355
FX9 Alloy				
Density	GPa	8360.4	8393.4	8376.9
Price	GBP/kg	1.12955	2.38223	1.75589
Youngs Modulus	kg/m³	119.52	148.74	134.13
Poisson's Ratio	-	0.3098	0.3321	0.32095
Tensile Strength	MPa	177.55	423.61	300.58
Elastic Limit	MPa	65.94	304.91	185.425
Shear Stress	MPa	47.65	55.2	51.425

Sub-material properties extracted using materials software package 'CES Edupack'.
Materials used: Copper, Tin, Zinc, Manganese, Aluminium.

Full Table of Results

B20 Alloy	Tests 1 - 5 - Frequency (Hertz)				
	1	2	3	4	5
Model 1 (Original)	81.407	82.468	93.491	95.209	193.77
Model 2 (Bend 10)	85.455	91.984	96.598	100.25	213.25
Model 3 (Twist 10)	72.272	86.313	87.262	99.218	218.1

B12 Alloy	Tests 1 - 5 - Frequency (Hertz)				
	1	2	3	4	5
Model 1 (Original)	83.298	84.383	95.721	97.483	198.26
Model 2 (Bend 10)	87.438	94.12	98.909	102.65	219.16
Model 3 (Twist 10)	73.96	88.335	89.332	101.59	223.36

B8 Alloy	Tests 1 - 5 - Frequency (Hertz)				
	1	2	3	4	5
Model 1 (Original)	84.213	85.309	96.802	98.586	200.43
Model 2 (Bend 10)	88.398	95.153	100.03	103.82	221.68
Model 3 (Twist 10)	74.777	89.313	90.336	102.74	225.91

MS63 Alloy	Tests 1 - 5 - Frequency (Hertz)				
	1	2	3	4	5
Model 1 (Original)	84.527	85.633	96.314	98.033	201.21
Model 2 (Bend 10)	88.741	95.5	99.409	103.16	219.29
Model 3 (Twist 10)	74.911	89.255	90.165	102.09	223.85

FX9 Alloy	Tests 1 - 5 - Frequency (Hertz)				
	1	2	3	4	5
Model 1 (Original)	89.291	90.46	101.59	103.4	212.51
Model 2 (Bend 10)	93.754	100.89	104.85	108.8	231.1
Model 3 (Twist 10)	79.115	94.192	95.207	107.68	235.97

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