Tyre cavity tones and road surface noise

an investigation using the

Tyre Cavity Microphone

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Abstract

The vehicle exhibits strong and easily heard tyre cavity resonance when driving at everyday speeds.
There are two modes for the primary tyre cavity resonance one along the shorter vertical axis, and the other on the longer horizontal axis. The shorter vertical mode will have a marginally shorter wavelength and hence a slightly higher frequency than the horizontal mode.
When running on the road the energy enters the tyre through the contact patch i.e. along the shorter axis the dominant mode is therefore at the frequency associated with the vertical stationary mode i.e. at the higher frequency.

When driving at 140kph the TCM is rotating at approximately 17Hz, the primary cavity mode is not shifted from the stationary frequency confirming that what is being measured is synchronous with the rotating TCM i.e. the air in the tyre is entrained and is spinning with the TCM. If this were not the case then the internal measurement by the TCM would be Doppler shifted. However the implication of this is that the forcing function applied to the axle will be subject to a Doppler shift. Inside the vehicle the primary cavity resonance, when detected, is indeed shifted upwards in frequency by the amount predicted.

The tyres fitted to the test vehicle are suspected as being the cause of the problem in-so-far as they generate unusually high levels of cavity noise. It is possible that these tyres may have been optimised for the ISO surface and are not suitable for "real" road surface quiet running.

Dynamic absorbers and suspension components should be tuned to the Doppler shifted primary cavity mode resonance input frequency rather than the statically determined primary cavity mode frequency.

Details of measurement (experimental set up)

The Tyre Cavity Microphone was positioned inside the tyre , attached against the rim using a stainless steel cable and high strength nylon tensioning straps, see figure 1. The TCM is controlled and transmits the data over a radio link. Typically for road noise route tracking each wheel carries a TCM; decomposition of the data gathered allows transmission paths to be ranked. Data was gathered, in this demonstration project from a single wheel, drivers front, at speeds from 50-140kph on two road surfaces, smooth and coarse asphalt.

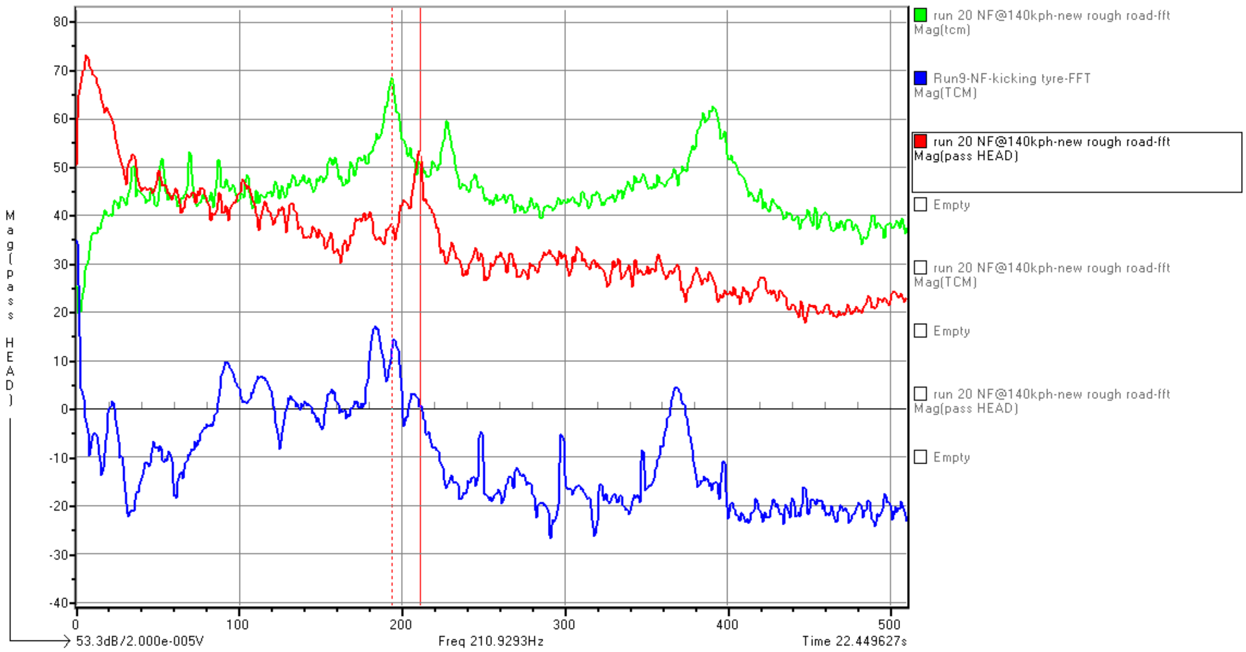
Figure 1. TCM attached to rim

Results of measurements

In figure 2 the blue trace is the result of kicking the stationary tyre when fitted to and loaded by the car. The cars load (approx. 600kg) will partially flatten the tyre, creating the contact patch, allowing two modes to exist, one vertical and one horizontal. However due to the construction of the tyre the overall circumference will remain the same, this generates two frequencies. The higher frequency measured, in this case, at 194Hz will be in the vertical direction and the lower 184Hz in the horizontal, see the blue trace in figure 2. The distribution of energy between the two modes is controlled by the point, in relation to the contact patch, at which the tyre is struck.

The vertical axis (dB level) is always unweighted , not Awt, and the scale is relative not absolute. This was necessary to allow publication of the data and protect the client(s) who supplied the car and tyres

Figure2. Cavity resonance frequencies measured inside the tyre cavity, using the TCM, & in the vehicle cabin.
Green = TCM 140kph Blue =TCM stationary Red = inside the car cabin @ 140kph



<u>At 140kph</u>

When running on the road energy enters the tyre through the contact patch and hence the tyre will generate the vertical response more strongly i.e. the higher frequency response at 194Hz will be dominant, as shown by the intersection of the red dotted red cursor with the green (TCM) trace, see figure 2. The second cavity mode when the wheel is stationary is at 368Hz, twice the horizontal modes frequency. However when running at 140kph the frequency of mode two is at 390Hz, twice the vertical primary mode frequency. Indicating that the pressure maximum is at the contact patch for all running cavity modes. Inside the car the primary cavity resonance peak, red trace, is at 211Hz considerably higher than 194Hz. The calculated frequency change, applying Doppler shift see below, would result in an expected frequency of 211Hz; i.e. very good agreement.

<u>Doppler shift</u>

<u>At 140kph</u>

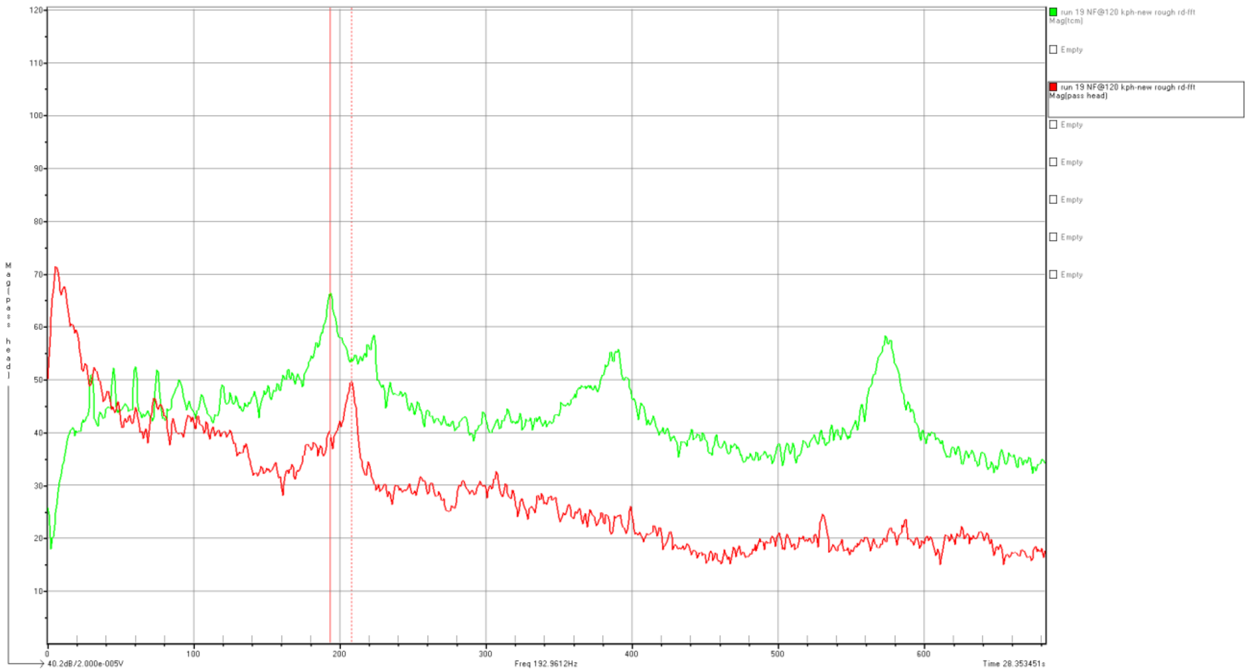
140kph = 38.88m/sec at the wheel circumference, speed of sound at a temperature of 320K (47 degrees C) and an inflation pressure of 2.5 Atm will be approx. 350m/sec. The acoustic wave is not however travelling on the tread circumference, rather it is at some mid point in the tyre annulus. A reasonable estimate would be at the midpoint inside the tyre i.e. at 83% of the tread velocity or 32.27m/sec.
The primary cavity resonance at 194Hz should be translated to 211Hz.

<u>At 120kph.</u>

The TCM cavity mode (green Trace), see figure 3, remains at 194 Hz (193.7Hz) while the passenger ear tone is now measured at 208Hz with the predicted frequency at 209Hz, again good agreement between predicted and measured.

Doppler shift @120kph
120kph = 33.33m/sec, speed of sound 350m/sec
mid tyre velocity is 83% of 33.33 =27.66m/sec
Change in frequency will be ((27.66+350)/350)194 = 209Hz

Figure 3. Cavity resonance frequencies inside the tyre and vehicle cabin at 120kph.
Green = TCM data from inside the tyre. Red = Front Passenger Ear



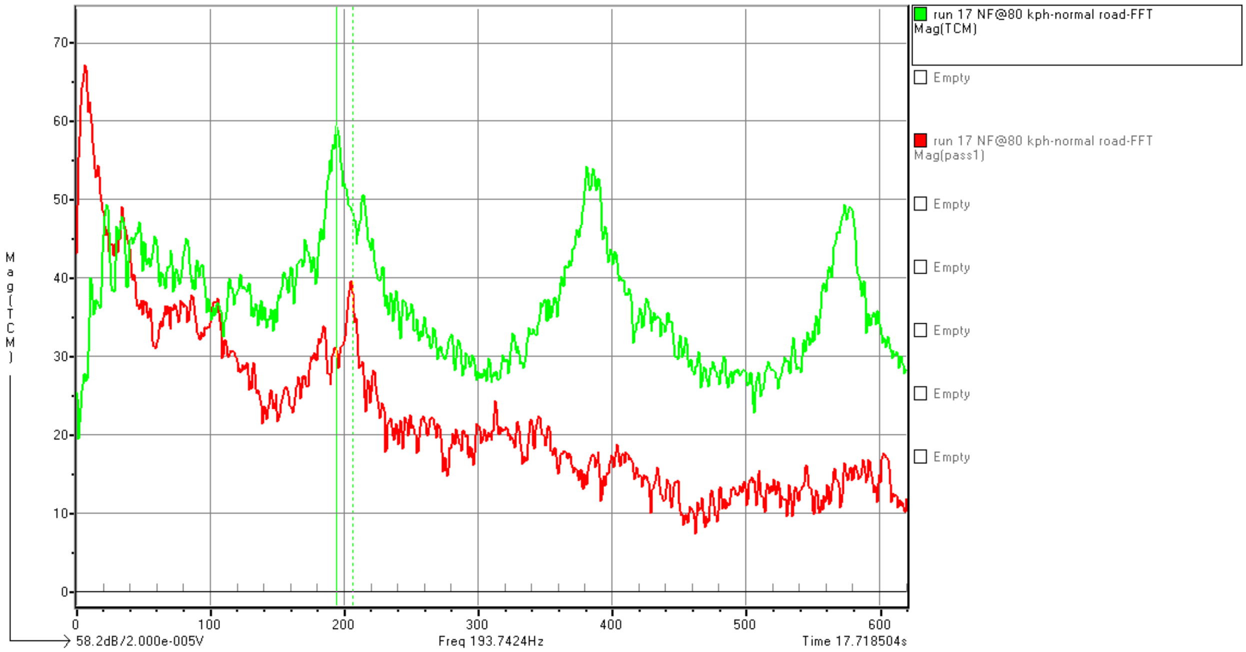
At 80kph

Reducing the speed to 80kph should again reduce the frequency of the primary cavity mode heard in the vehicle's cabin due to a reduced Doppler shift.
The primary cavity mode measured in the tyre remains at 194Hz (193.7), see the green trace in figure 4. The frequency in the car's cabin is however measured at 204Hz with the predicted frequency also at 204Hz; again very good agreement.

Doppler shift
80kph = 22.22m/sec reduced by 83% = 18.44. The speed of sound 350m/sec inside the tyre
Change in frequency will be ((18.44+350)/350)194 = 204Hz
The in tyre tone at 194Hz should be translated to 204Hz, inside the car's cabin

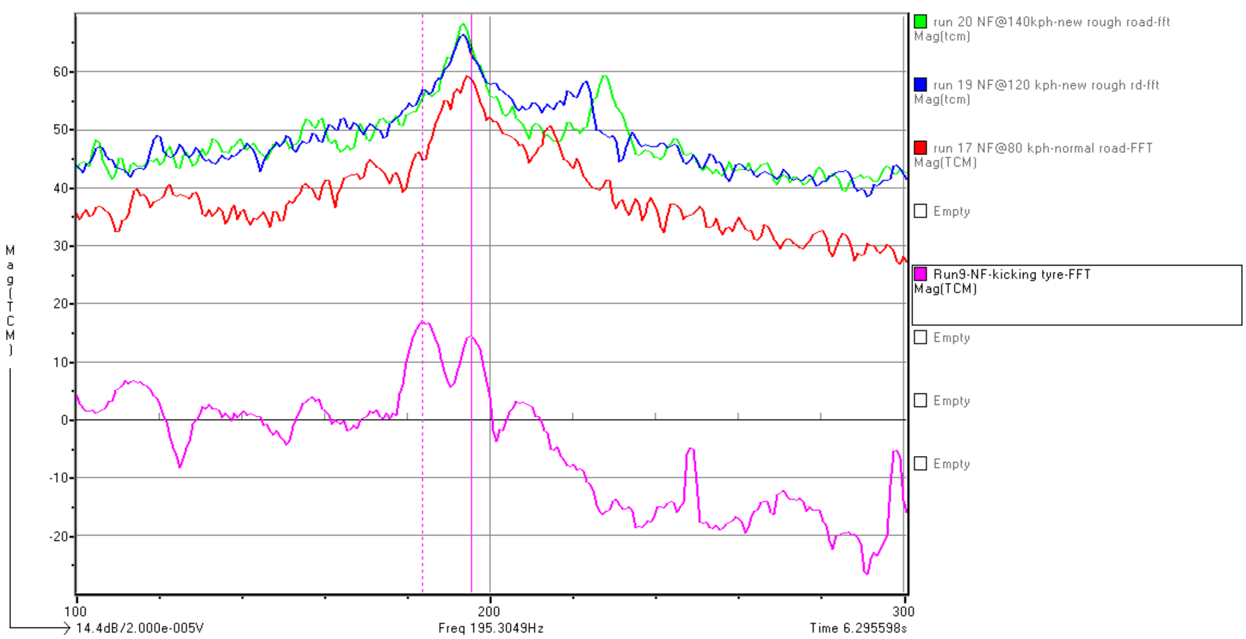
The good agreement between measured and predicted cabin tone frequency for the three test speeds provides confidence that the hypothesis for the frequency offset mechanism is valid.

Figure 4. Cavity resonance frequencies inside the tyre and vehicle cabin at 80kph.
green = TCM   Red = Front Passenger Ear



Comparing the in tyre data at the three speeds 140/120/80kph, see figure 5, the frequency of the primary cavity mode can be seen to be constant, within a tolerance of 1Hz.

Figure 5. Cavity resonance measured inside tyre at 140/120/80kph & when stationary
Green = 140kph   Blue = 120kph   Red = 80kph   Magenta = Stationary



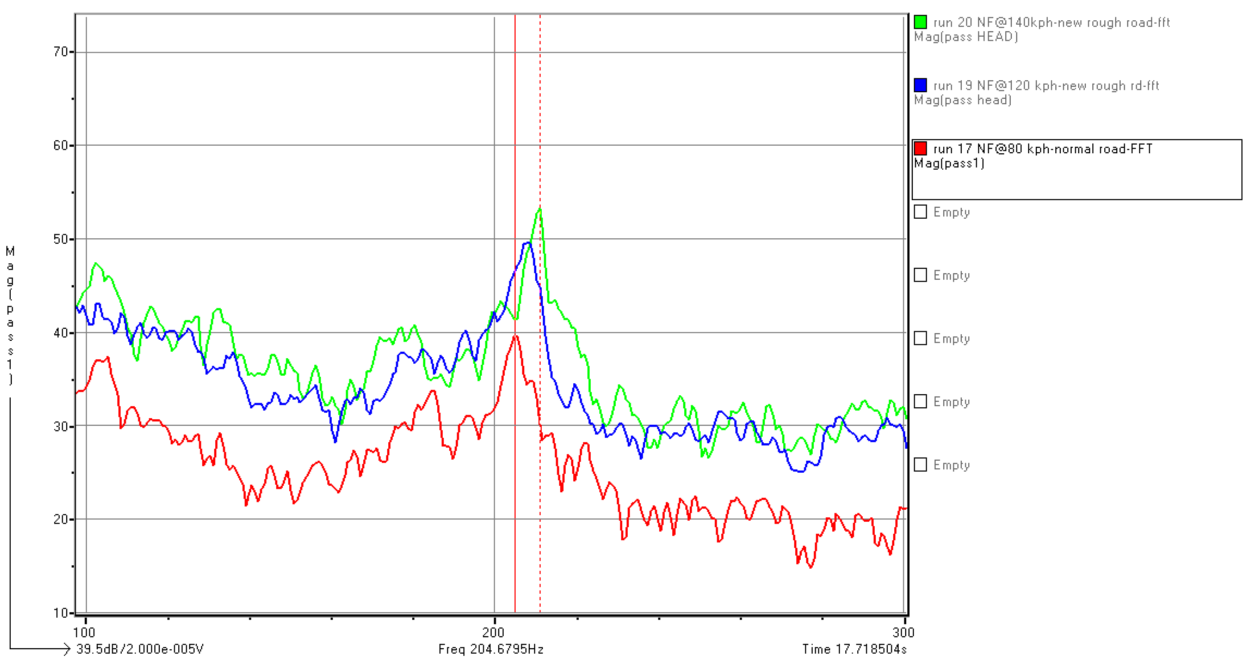
The response (amplitude) inside the tyre is a function of the amplitude of the forcing function. The relatively gentle tap with the foot, to allow the extraction of the cavity mode resonance frequencies is shown to be some 40+dB lower than the running tyre response to road input.

Inside the tyre the primary cavity mode frequency is essentially unchanged by the speed of the car when measured by the TCM i.e. in the frame of reference of the spinning wheel.

The slight increase in the cavity mode frequency at 80kph can be explained by the slightly larger contact patch and hence shorter wavelength, and higher frequency. This is due to the reduction in centripetal force and the tyre becoming less round at lower speeds. When the car is stationary the contact patch is a maximum and so the frequency should be the highest and at 195.3Hz it is, see the Magenta trace in figure 5.

Inside the vehicle's cabin the primary cavity frequency does increase in frequency as the speed of the car increases, see figure 6. However as the transmission of the tone is almost certainly through the structure of the car rather than through any airborne path the increase in frequency must be a Doppler effect. This must be occurring inside the tyre but is nullified in the TCM data by the spinning of the TCM. If there were, as is sometimes suggested, two equal cavity mode waves propagating in opposite directions, then the TCM data would contain two equal peaks separated at 140kph by some 30Hz. The second upwardly shifted cavity wave is indeed seen in this data at approximately 230Hz, see figure 5, but at nearly 10dB lower amplitude. The presence of a second contra-rotating cavity mode wave allows for the possible generation of a low frequency beating; which in turn might couple in some way with the wheel rotation harmonic series and drive low frequency cabin modes.

Figure 6. Cavity resonance frequencies measured at front passenger head inside cabin @ 140/120/80kph.
Green = 140kph Rough Asphalt Blue = 120kph Rough Asphalt Red = 80kp Smooth Asphalt



The 80kph run completed on the older smoother asphalt was significantly lower in level than runs completed on the new rough asphalt. Plotting the in tyre and cabin levels for 50/80/120kph for the smooth asphalt reveals that at 50kph the primary cavity resonance is at a greater amplitude than at 80 and 120kph, see figure 7 & 8.

Figure 7. Cavity resonance frequencies measured inside tyre at 50/80/120kph on smooth asphalt
Green = 50kph Blue = 80kph Red = 120kph

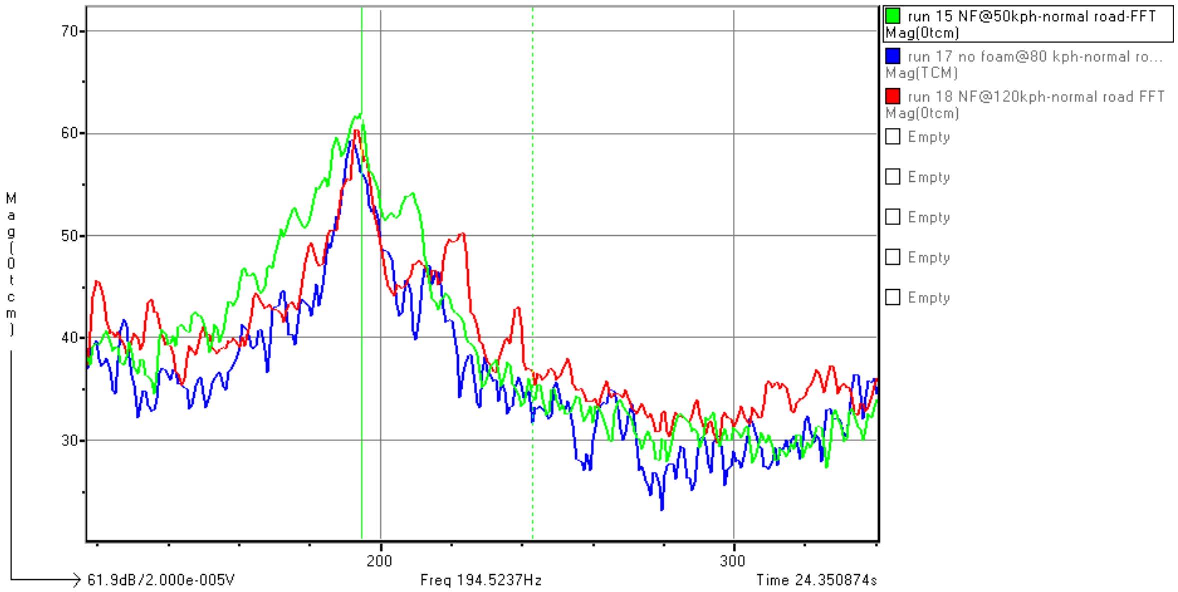
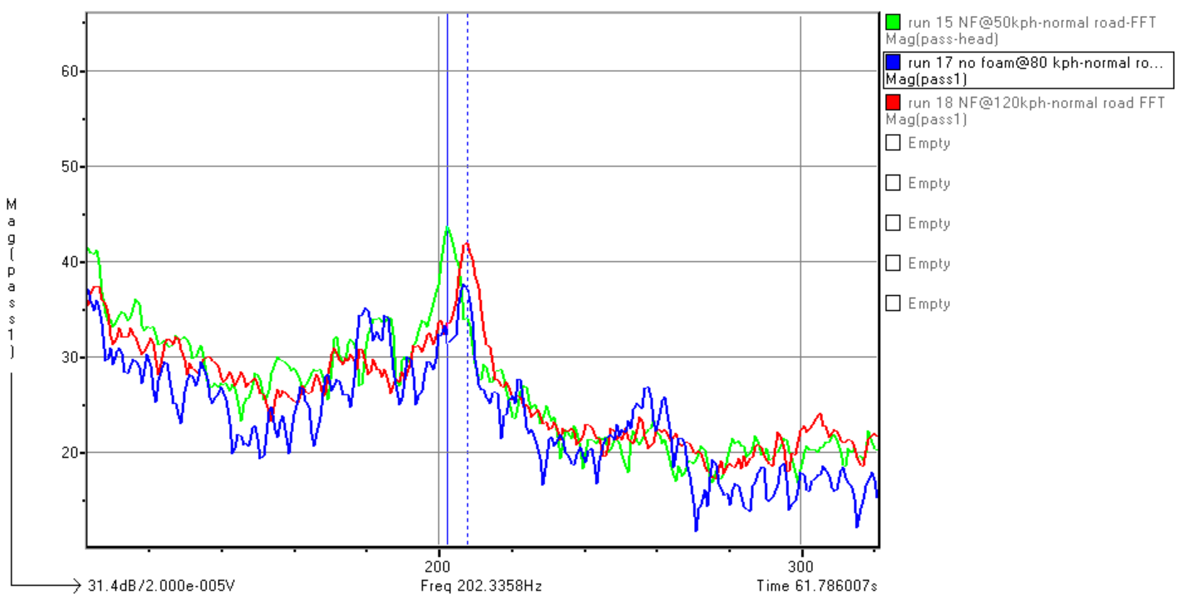


Figure 8. Cavity resonance frequencies measured inside cabin at 50/80/120kph on smooth asphalt
Green = 50kph Blue = 80kph Red = 120kph

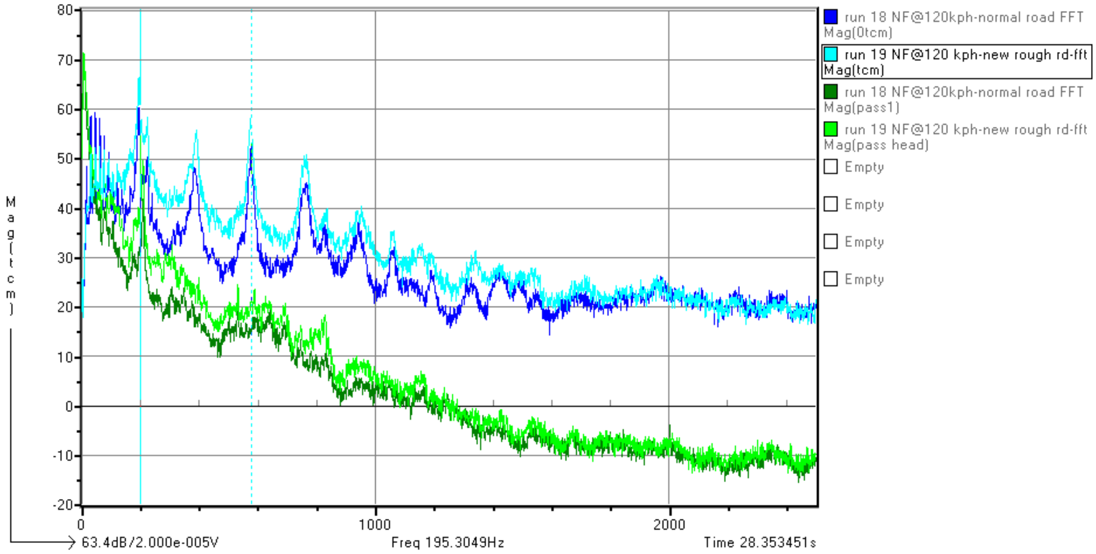


Affect of road surface @ 120kph

The only speed at which measurements were made for both rough new asphalt and the older smooth asphalt was 120kph, see figure 9. Of particular interest is the strong visual correlation between TCM and cabin levels up to 600Hz, but not for cavity modes > 1. Above 600Hz the cabin noise (green traces) the visual correlation is not so strong, the TCM data does still reflect the higher input from the rougher surface (blue traces). Above 1800Hz neither the TCM or cabin data is obviously affected by the rougher surface.

Figure 9. TCM and Cabin levels for smooth and rough asphalt (blue = TCM Green = cabin)

Cyan = Rough TCM Blue = Smooth TCM LGreen = Rough Cabin DGreen = Smooth Cabin

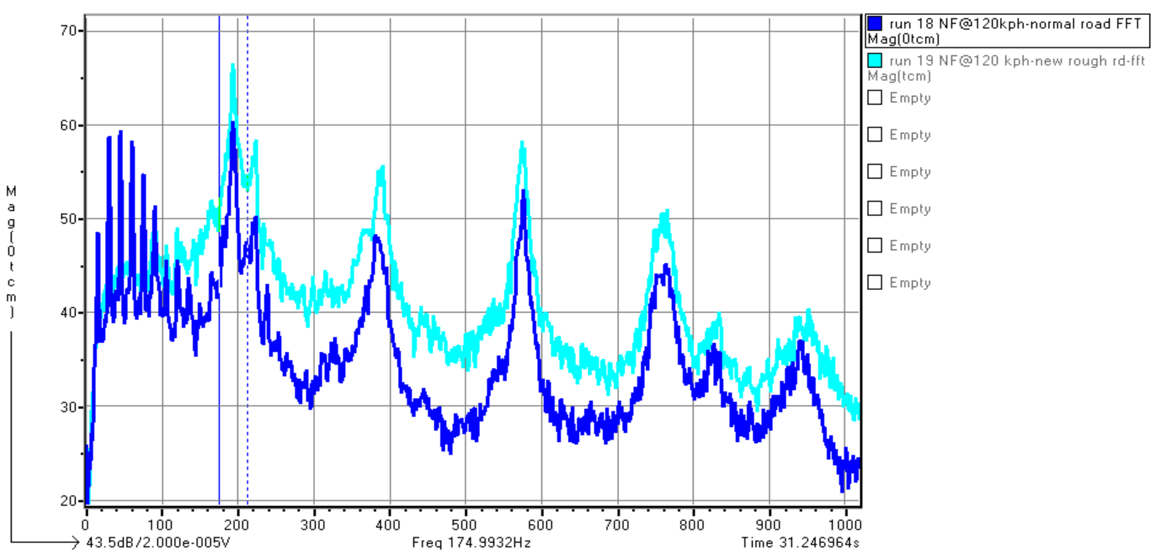


Tyre primary cavity mode - comparing smooth and rough asphalt surfaces

Inside the tyre the rougher surface is clearly noisier (cyan), see figure 10. However the presence of wheel rotation orders should be noted as these are known to drive the cavity modes.

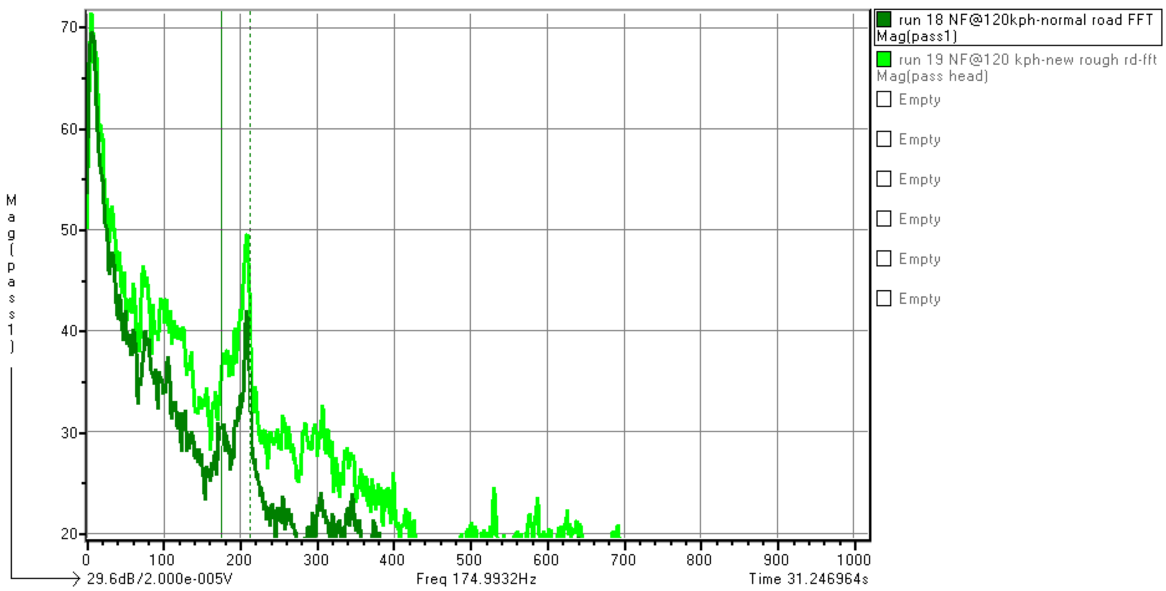
Figure 10. The primary cavity mode measured inside the tyre @ 120kph on smooth & rough asphalt.

Blue = Smooth asphalt Cyan = Rough asphalt



The cabin noise levels reflect the increase in TCM level when going from smooth to rough asphalt for the primary cavity resonance, see figure 11.

Figure 11. The primary cavity mode measured inside the cabin is 7dB higher on the new rough asphalt
Dark Green = Smooth asphalt Light Green = rough asphalt



Discussion

The results obtained using the TCM show the high level of the primary cavity mode at 50kph. The level of the 50kph primary cavity mode was higher than the 80 and 120kph levels; this is unusual and would normally be ascribed to poor tyre design.

Further work and measurement is recommended to resolve exactly what is driving the high level of the primary cavity mode at 50kph.

A simple check to separate suspension and body coupling from tyre input would be to fit another manufactures tyres to the car and repeat the measurements. If the tyre size is unique then it may be necessary to use a none standard wheel and tyre size and adjust the speeds correspondingly.

This substitution would be inexpensive and should be very revealing. The other useful way forward would be to measure the current tyres in a laboratory. The tread and resonance, cavity and structural would then be obtained and could be compared with other tyres. This would provide evidence that would be used to guide the way forward towards a road/tyre noise solution for this vehicle.

Conclusions

The contact patch decreases marginally as speed increases; the effect is too slightly lower the frequency of the dominant, vertical, primary cavity mode. The frequency heard inside the car is shown to be modified by the Doppler shift.

The change in level of the TCM data exactly matches the change in level measured inside the vehicle's cabin i.e. force in at tyre = noise heard inside vehicle
Tuning of the suspension to avoid the primary cavity resonance should take account of the Doppler shifted input frequency rather than be based upon the natural cavity mode frequency.

The fading in and out of the primary cavity mode tone, heard in the vehicle's cabin, might be attributable to a number of mechanisms : -

1. The tread input forcing function combined with the wheel rotation orders track through the primary cavity resonance modulating the input to the axle.

2. The changing phase relationship between the cavity modes in each wheel create a vector sum input to the body. This can amount to a force input of some 200N. (this number is based upon the +/- 500Pa peak pressure and the surface area of the wheel rims)

3. The primary cavity mode that generates the driving force at the axles will couple more or less effectively with suspension and body if these have a high Q.

The level of the primary cavity mode inside the tyre and in the cabin was higher at 50kph than at 80 and 120kph. This is not a common result, normally the cavity mode level inside the tyre, at 50kph, is half the level at 100kph. It is very unusual for a cavity to respond with a higher amplitude at 50kph than at 100kph.

The effect on noise inside a vehicle of road surface change from smooth to rough, as experienced by all drivers, is shown to be significant at frequencies below 1kHz. The new rougher asphalt surface injects a great deal more energy into the tyre, in consequence the cavity mode peak levels and general background levels go up by approximately 7dB. Inside the vehicle's cabin the noise level also increases by 7dB.

It is known that a tyre designed to perform well on the ISO pass-by surface can perform badly on "real" roads. This possibility should be examined carefully by performing the suggested tyre swap and repeating the tests.

N.B.
The test work described in this technical note was completed in a morning with two additional days spent on analysis and reporting.

End

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