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Airless tires in the LEON-T project: How can they reduce tire/road noise emission

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ABSTRACT

For more than a century, pneumatic tires (inflated with air) have totally dominated the market for road vehicle tires. However, in the recent two decades, interest has grown in developing airless tires; tires whose load is not carried by the inflation by air, but by the mechanical structure that connects the belt and rubber tread with the hub. The EU project LEON-T includes a part in which prototypes for innovative heavy goods vehicle (HGV) tires are developed, with the main purpose to reduce noise emission by 6 dB. To reduce noise that much it is believed that airless tires are needed.

In LEON-T, two airless tire prototypes are intended to be developed by partner Euroturbine, in cooperation with other partners and subcontractors. Originally, the load-carrying material was intended to by composite material (reinforced plastic), but initial calculations have shown that a stronger material is needed; consequently, steel springs are currently being used.

This paper will describe the principle of airless tires but with focus on the version being developed in LEON-T. The main part of the paper will deal with the noise generation mechanisms and the ways that airless tires can reduce the noise emission are thoroughly identified and discussed.

1. INTRODUCTION

It is often claimed that the pneumatic tires as we know them today are the most complex component of a road vehicle. For example, today's typical tire is an incredibly sophisticated product; an average tire for cars and trucks contains well over 100 separate components of various materials. This is a result of over 100 years of intensive R&D by the industry. Why has no other kind of tire outpaced the pneumatic tire in these 100+ years? The arguably first attempt was presented by Goodyear engineers in 1989 [1] when a "Composite Integral Wheel-Tire" was described, which was "air-free". About the same time and unknowing of the Goodyear design, Swedish chief engineer Hans-Erik Hansson attempted to develop low-rolling resistance and puncture-free tires for sulkies and competition bicycles. He called his tire "The Composite Wheel", but it was in fact an airless tire.

In the time period 1989-2008 this author led projects with the aim to develop prototypes for airless car tires [2,3], the designs of which were based on the inventions of Mr Hansson, nowadays active in his company Euroturbine AB, who also led the manufacturing work. It was immediately realized that the design in all its versions had an excellent potential to reduce tire/road noise emission; later it also was shown to have an even greater potential for reducing rolling resistance.

This paper deals with the noise emission property of the airless tires; especially the Hansson designs, but the principles of noise reduction would be valid also for other airless tire concepts being presented in the last 20 years. It is based on both the earlier experience of the "Composite Wheel" (CW) as well as the ideas behind the design presently being developed in the EU project LEON-T [4]. This is, again, a cooperation with the inventor, Mr Hansson, but also supported by a Swedish company named Lightness by Design and by modelling work by Spanish company Idiada.

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2. TERMINOLOGY

Pneumatic tires or *air-inflated tires* are tires where air or another gas is contained in a torus inflated sufficiently to carry the load applied to the tire. This is the totally dominating tire type on today's road vehicles.

Airless tires are tires where a solid, flexible material such as rubber, reinforced plastic or metal (separately or in combination), transfer the vehicle load from a rim (or directly from an extended hub) to the circumferential belt on which a rubber tread sits. Essentially it replaces the flexible tire sidewalls and inflated air. Other terms used are *air-free tires* or *non-pneumatic tires*. This author prefers the simple term *airless tires*.

Note that the term *tire* is the American way of spelling the British word *tyre*.

3. PURPOSE AND LIMITATIONS

The paper attempts to answer the question "how can airless tires reduce noise emission in ways not possible by pneumatic tires", and what kind of features of airless tires may counteract this noise reduction. To do this it is necessary to review the tire/road noise generation mechanisms as they may operate in pneumatic versus airless tires.

Since there are many concepts for airless tires, this paper focuses on the concepts based on Mr Hansson's design; i.e. the one produced 15-20 years ago for car tires and the one being produced in the ongoing LEON-T project which is for heavy truck tires. Other airless tire concepts may not have all the noise-reducing advantages of the tires considered here.

Note that this paper deals only with the noise emitted externally from the tires. A more general description and discussion is found in [5], and a state-of-the-art report in LEON-T is available in [6].

4. TIRE DESIGNS CONSIDERED

4.1. The "Composite Wheel" produced 2003-2008

The final design in the project 2003-2008 is shown in Figure 1 [3]. The next figure shows the tread from above, in which case one can see the circular holes at the bottom of the longitudinal grooves and which go all the way through the belt (Figure 2).

Figure 1: The Composite Wheel according to the last version produced in an earlier project. The left half shows the side facing outwards from the car, the right half facing inwards. From [7].

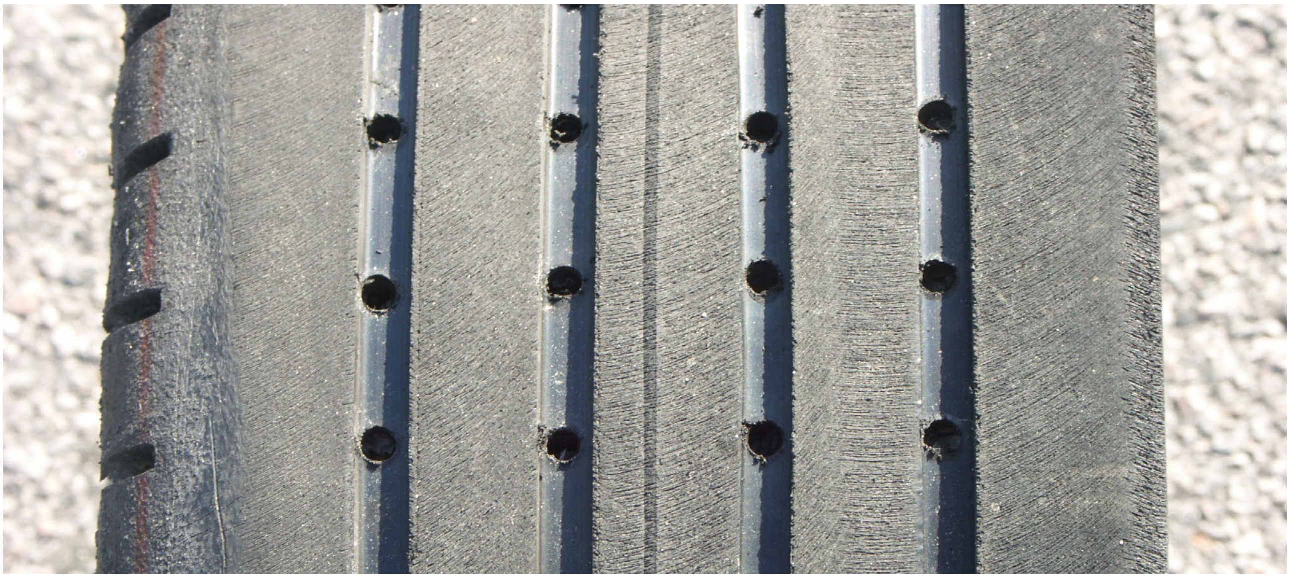

Figure 2: The tread shown from above. Note the circular holes at the bottom of the longitudinal grooves which are drilled through the belt. The holes have a diameter of 6 mm and are 30 mm apart.

The material is a prepeg composite glass-fiber/polyester laminate in the spokes, the rim and the belt with a rubber tread on the circumference. The Composite Wheel was intended to replace regular tires of dimension 225/45R17 91 or 205/55R16 91V.

4.2. The LEON-T preliminary design

In the LEON-T project the present plans are a design as indicated in Figure 3. Note that in the left part of the figure there are holes in the bottom of the longitudinal grooves that are drilled through both the rubber and the belt.

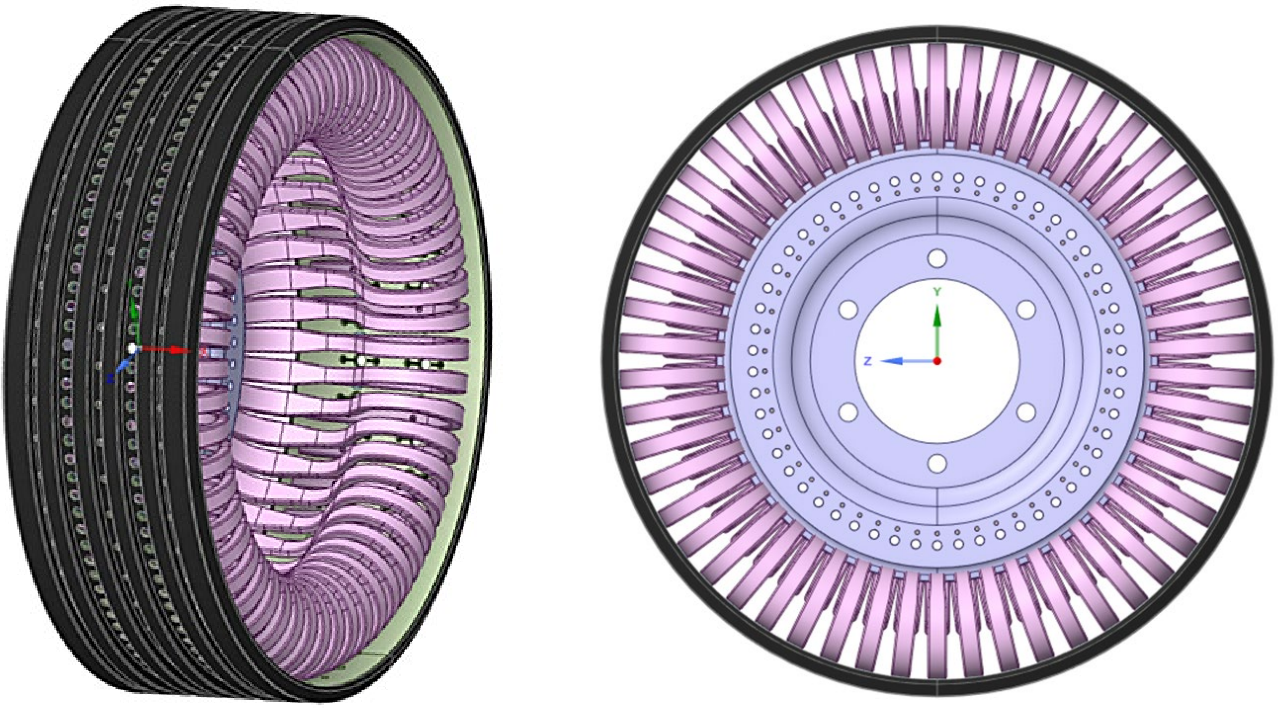

Figure 3: The airless truck tire, as planned to be constructed in the LEON-T project. Note that the final design may look different, but the principal design should be the same.

The materials in the airless tire will be the following:

- Rim of (fossil-free) steel
- Spokes by (fossil-free) steel
- Belt in composite glass-fiber/polyester laminate
- Tread of rubber obtained from project partner Linglong Tires.

The reason for using steel in the spokes instead of the composite material used in the earlier car tire is that initial calculations and simulations showed that the composite material was not strong enough to carry the dynamic loads of a truck tire. The airless tire is intended to replace regular truck tires of dimension 285/70R19.5, with load index 141/143, typically used on 16-20 ton heavy trucks.

The aim is that this tire shall produce 6 dB less noise emission that regular tires of the targeted dimension. Two prototypes should be produced, one for the steering and trailer axles, and one for the drive axles of heavy trucks. The only difference between the two will be the tread pattern, where the drive axles will require some cross-grooves to provide appropriate traction. The steering wheel prototype will essentially have a pattern with straight longitudinal grooves, with sipes in the diagonal directions, intended to provide more flexible stick-slip motions in the contact patch. Drainage of water relies not only on grooves in the tread pattern but also on holes through the tread and belt. This feature seems to be unique in the airless concepts presented so far.

5. PROJECTED NOISE GENERATION MECHANISMS

5.1. For regular pneumatic tires

Figures 4 and 5 illustrate the various noise generation mechanisms of conventional air-inflated tires. One can distinguish between those which create vibrations in the tire which are turned into sound waves and those who create air pressure gradients which are turned into sound waves. The latter include also some phenomena which are not really generation mechanisms but rather are amplifying mechanisms. In Figure 5 those are cavity resonances in the tire torus, pipe resonances, the horn effect and air-resonant radiation. The major generation mechanism in Figure 5 is only the so-called “air-pumping”, where air is pumped out of the tread and surface interface at the leading contact edge and sucked in at the trailing contact edge. In Figure 4, all the vibration mechanisms may combine and create vibrations in different directions in the tire tread elements and in the belt and sidewalls of the tire.

All mechanisms tend to radiate significant sound from near the contact patch, both in the tread and the sidewalls, within a decimeter from the contact patch—closer for high frequencies and further away for low frequencies. The two most important mechanisms are generally considered to be the radial vibrations either caused by texture in the surface or by tread elements, and the air-pumping, amplified by the horn effect and pipe resonances. The cavity resonance in the tire tube is insignificant exterior to the tire.

5.2. Analogy of air-inflated tires with loudspeakers in a cabinet

There is a certain analogy between an air-inflated tire and a loudspeaker in an enclosed cabinet. Consider a domestic hifi system with an 8” loudspeaker unit mounted inside a cabinet of (say) 3x4x2 dm = 24 dm^3 (liters). Play and listen to some music with high levels of bass notes. Then open the cabinet and remove the 8” loudspeaker unit from it. Play the same music again, now through the loudspeaker free in the air. You will hear almost no bass notes. This is because the sound pressure from the front of the loudspeaker diaphragm is cancelled out by the opposite from behind the diaphragm which at relatively low frequencies (long wavelengths, say, longer than the 8” loudspeaker) are 180 degrees out-of-phase with each other. One may consider the loudspeaker and cabinet unit as an acoustic monopole at relatively low frequencies, while the loudspeaker without any enclosure will be a kind of dipole source, which is a much less efficient radiator at low frequencies.

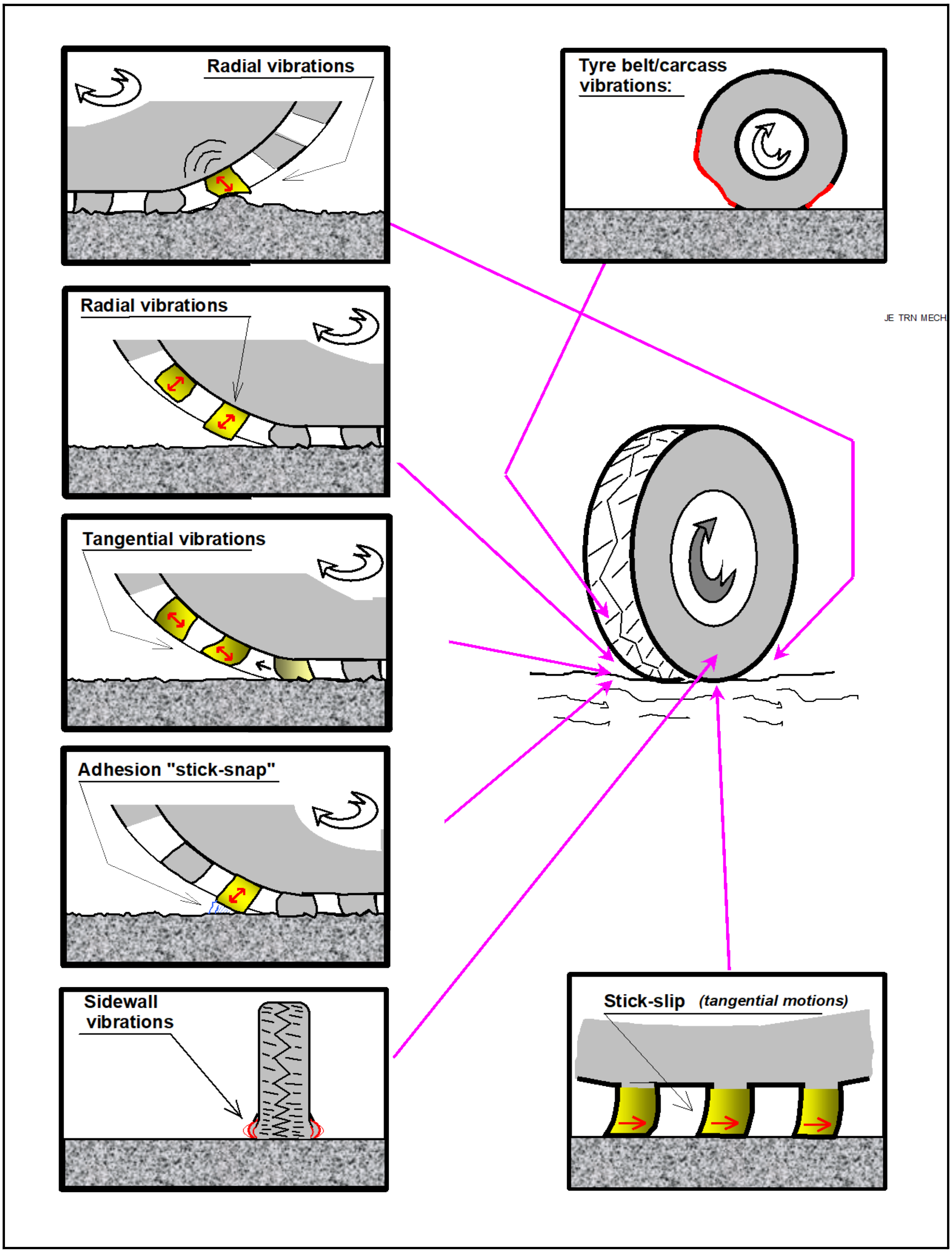

Figure 4: Vibration-related noise generation mechanisms for general air-inflated tires. From [7].

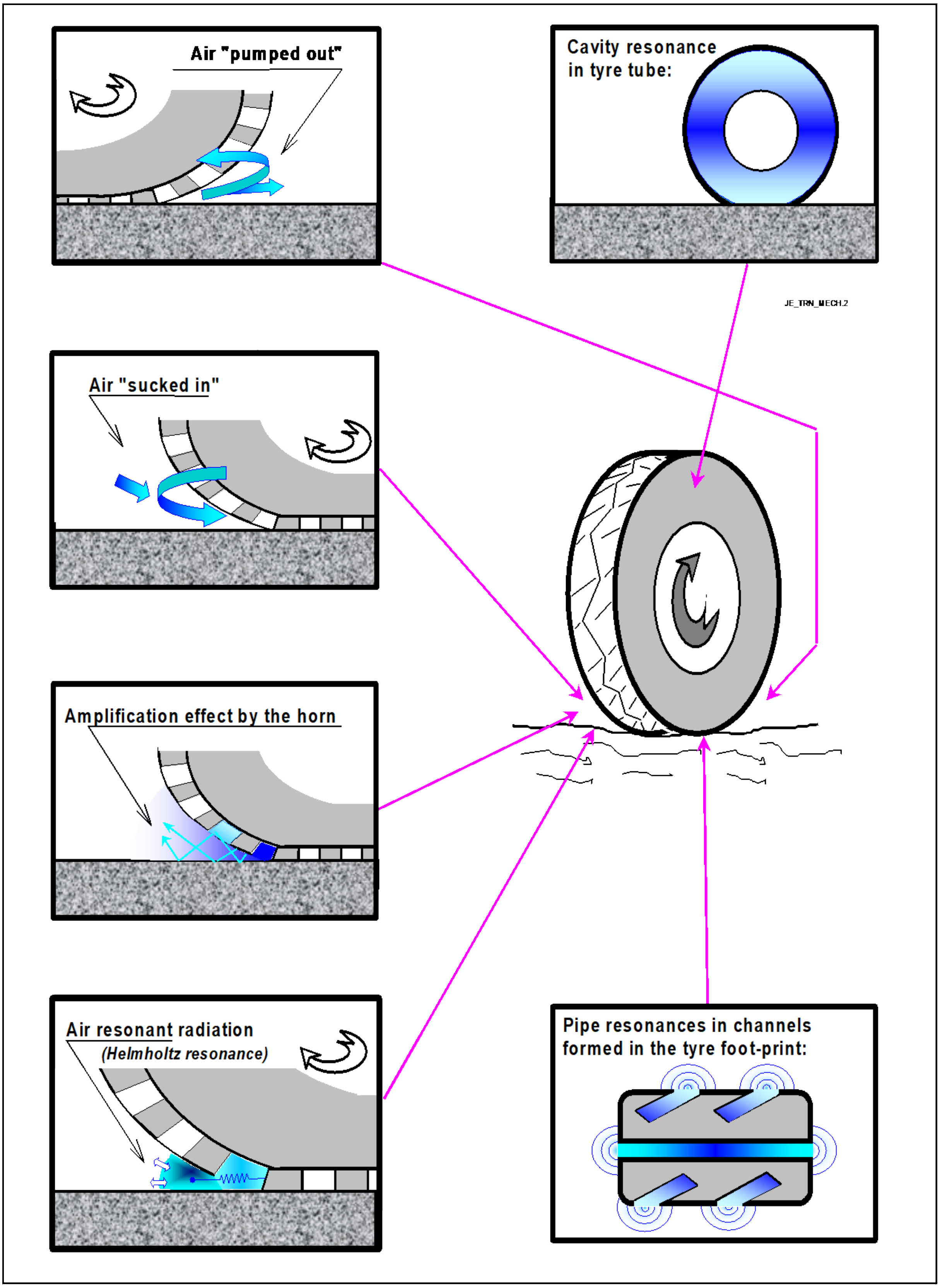

Figure 5: Aerodynamic-related noise generation and amplifying mechanisms for general air-inflated tires. From [7].

At high frequencies (say, wavelengths around the size of the 8" loudspeaker), the opposing phase-relation is lost due to the loudspeaker acting as a baffle separating some of the air pressure from both sides, so there will be a net sound pressure which is not cancelled out.

Then consider a passenger car tire, say a dimension 205/55R16, as we had as a reference tire in the earlier Composite Wheel project. The tire sidewalls and tread close to the contact patch may be considered as diaphragms that vibrate and create air pressure variations (sound pressure) close to the contact patch, which sit in an enclosed toroid volume. The air volume of such a tire is roughly around 24 dm^3, so it is a fair analogy to the loudspeaker in its cabinet mentioned above. Such vibrating membranes (tire sidewalls and tread) will be quite good sound emitters at low and medium frequencies, thanks to the air pressure variations on the inside of them are protected from balancing out the same on the outer side by the enclosure.

For a truck tire of dimension 285/70R19.5, the enclosed air volume is around 100 dm^3, which corresponds to a professional or studio loudspeaker/cabinet unit.

5.3. Airless tires compared to loudspeakers in boxes

In an airless tire, there is no enclosure that protects the air pressure from behind the diaphragm to balance out the air pressure from the other side. The low frequencies (bass notes) will be partly cancelled out, more or less effectively depending on the wavelengths. This is equivalent to a so-called dipole situation. Even the tread and belt structures are “transparent” to air pressures as there are holes through them.

Any large dense structures, such as the rims in Figures 1 and 3 may act as “baffles” for medium-to-low frequencies, but as they are fairly rigid and not so likely to vibrate in perpendicular directions, they may not be too important sound radiators. Nevertheless, one shall not neglect them, especially, as there may be vibration resonances in the spokes that may excite both the rims and the treads.

The conclusion is that airless tires are relatively poor sound radiators at low and medium-to-low frequencies which are created by the vibrational mechanisms illustrated in Figure 4.

5.4. Aerodynamic mechanisms and amplifiers for airless tires

When it comes to the aerodynamic mechanisms, which are important at medium and high frequencies, the comparison between air-inflated and airless tires has certain common features to the situation at low frequencies. Those mechanisms create air pressure gradients in and around the tire/road contact patch which result in sound pressures at relatively short wavelengths. For an airless tire with holes through the tread and belt, the air pressure gradients will be substantially reduced as air is pumped through the holes to or from the inside of the belt.

Also, the amplifying mechanisms will be “short-circuited” by the belt and tread not being solid and tight, but partly transparent or porous. For example, the horn effect relies on the sound coming out of a “throat” between solid walls--one being the curved tread and the other being the road surface. If either one of these walls are porous or perforated, the horn will lose its effect. However, this is the case only for the airless tires described in this paper, while other airless tire concepts being presented so far do not seem to have this feature, as far as this author has understood it.

Nevertheless, also with holes in the tread and belt, there will be air pressure variations sufficiently strong to emit significant sound; albeit much reduced compared to air-inflated tires.

5.5. Noise components special to airless tires

Acoustically, all is not well for airless tires. The spokes may radiate sound, like a very thick string, but they may also interact with structures they connect to, such as the tread/belt and the rim (like strings in an acoustic bass guitar interacts with its sounding board and wooden case). In general, the vibration of a string alone is barely audible, but when it connects to a board it may create substantial sound emission, unless the board is heavily restricted. For air-inflated tires, rims are considered as negligible noise sources, but in airless tires like in Figures 1-3 one must not forget them. Preliminary simulations/modelling have indicated that the spokes in the Composite Wheel in Figure 1 have a resonance around 400 Hz which appears in recorded frequency spectra, and for the airless tire design of Figure 3, the spokes also have a resonance around 400 Hz (results to be published later).

Probably more important as a vibrational source is the impact of the tread on the road surface, hitting the points above each spoke connection as compared to the areas between the spokes. The mechanical stiffness of the system will then vary with a frequency of the "spoke impact" since the area just on top of each spoke is stiffer than the area between the spokes. This effect is virtually null for air-inflated tires due to the stiff metal rim which the tire sits on.

The spoke impact period for the truck tire design shown in Figure 3 will be determined by the number of spokes and the diameter of the tire. In this case, it will be the tire circumference (2.73 m) divided by the number of spokes (54), which results in a distance of 50 mm between each spoke impact. This distance will correspond to potential vibrations and resulting sound at approximately 277 Hz at 50 km/h and 440 Hz at 80 km/h.

For an air-inflated tire these frequencies and the range around them (including potential harmonics) could become a serious problem, but for an airless tire with its dipole-type radiation, due to its open structure, the sound radiation would be less important although in no way negligible. In particular, the case may become a problem when the spoke impact frequency coincides with the spoke resonance, which may happen for speeds around 75-80 km/h.

For the Composite Wheel in Figures 1-2, the circumference is approx. 1.93 m and the number of spokes is 64, which results in a distance of 30 mm between each spoke impact. This distance will correspond to potential vibrations and resulting sound at approximately 463 Hz at 50 km/h and 740 Hz at 80 km/h.

6. NOISE EMISSION AS OBSERVED IN THE COMPOSITE WHEEL PROJECT

Figure 6 shows how little the Composite Wheel spectral shapes change with speed. The spectra are changed a lot by the speed but only as a parallel shift. There is also a very pronounced peak at 400 Hz for all speeds. This tells us that the spoke impact has no significant effect, as it should show a peak proportional to speed, but there is a structural problem which is independent of speed.

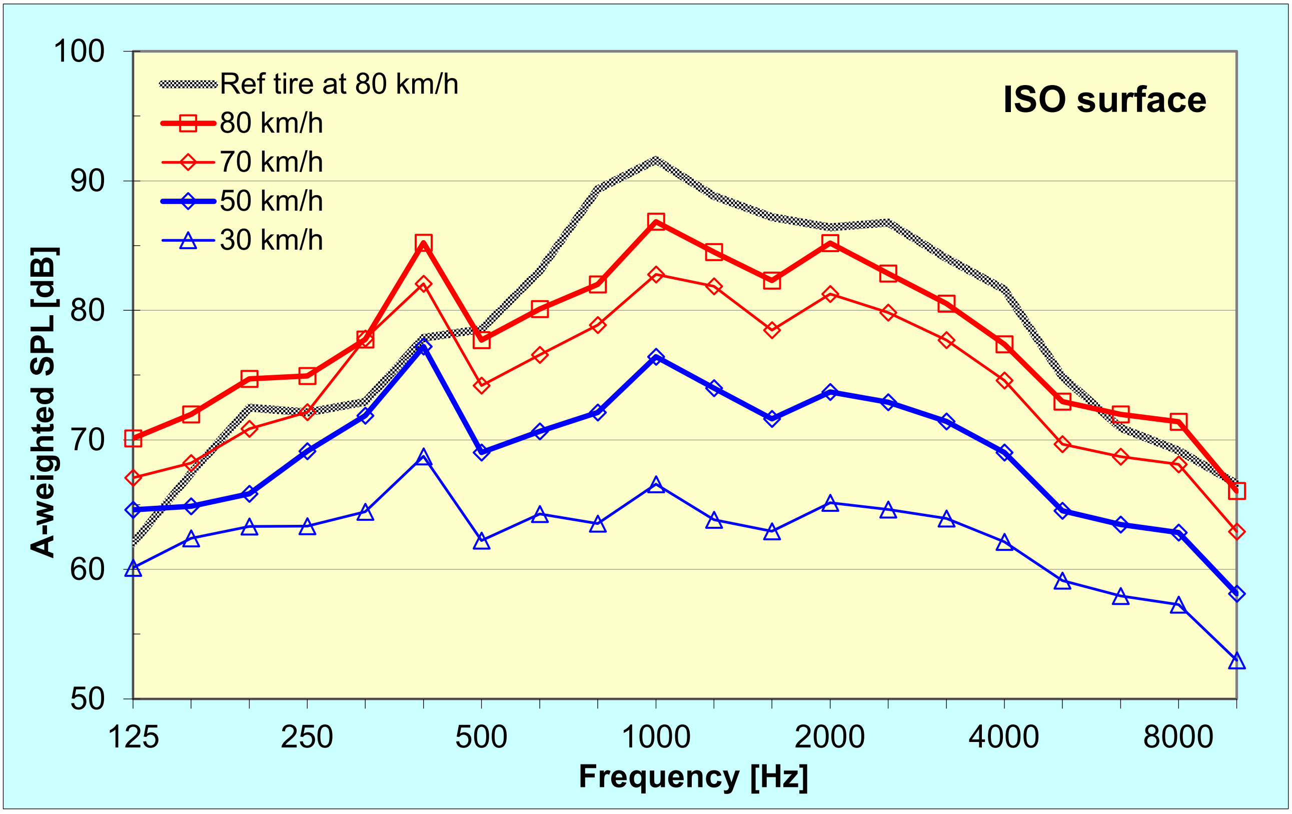

Figure 6: Frequency spectra for the last Composite Wheel prototype for four test speeds, measured in 2007 with the drum method on an ISO replica surface. For comparison, also the spectrum for the reference tire (Nokian Hakka V) has been included but only for the speed of 80 km/h.

This structural problem can be referred to the structural mode noticed at around 400 Hz in analyses made in 2022 on the tire prototype by Idiada (not yet published). This is influencing the overall A-weighted level significantly; especially at low speeds where the 400 Hz band is the highest.

Then Figure 7 shows the effect of grooving the tread pattern and drilling holes in the grooves, through the belt. The half-wavelength pipe resonance should be in the range of 1100-1600 Hz (depending on the contact length, which unfortunately was not measured), and there is no sign of this in Figure 7. The structural resonance at 400 Hz is very pronounced and it seems like there is also one in the 1000 Hz band, perhaps even with a harmonic at 2000 Hz. What is really interesting is that with no sign of groove influence (pipe resonance) the holes seem to be the explanation for reducing noise levels all over the frequency range. This was also a conclusion by [8]. It must mean that the tread is responsible for quite an important part of the sound radiation, which is influenced by the holes. It is certainly not responsible for all the sound radiation since the structural resonance(s) is prominent even with the holes.

At the high frequencies, the holes eliminate most of the air pumping and its amplifying mechanisms (by 5-6 dB) but at 6300 Hz they provide no significant effect. It would be interesting to identify the reason for the effect at 6300 Hz, which corresponds to a wavelength of 54 mm, where half of this wavelength (27 mm) could have a relation to the spacing between the holes, which was about 30 mm. It would actually fit the pipe resonance of the open pipe existing in the grooves between the holes, as described in chapter 7.1.17 in [7].

The two tires in Figure 7 were not entirely identical (in addition to the grooves and holes). The non-patterned tire had 2 Shore A units higher rubber stiffness, but this should give less than half a dB higher noise levels and should therefore not influence the conclusions. It shall also be mentioned that the choice of the ISO surface for these tests are based on two advantages: (1) it is a kind of surface generally used for testing tire/road noise, and (2) it tends to highlight differences between tires since the road surface texture effects do not obscure the results as much as rougher surfaces do.

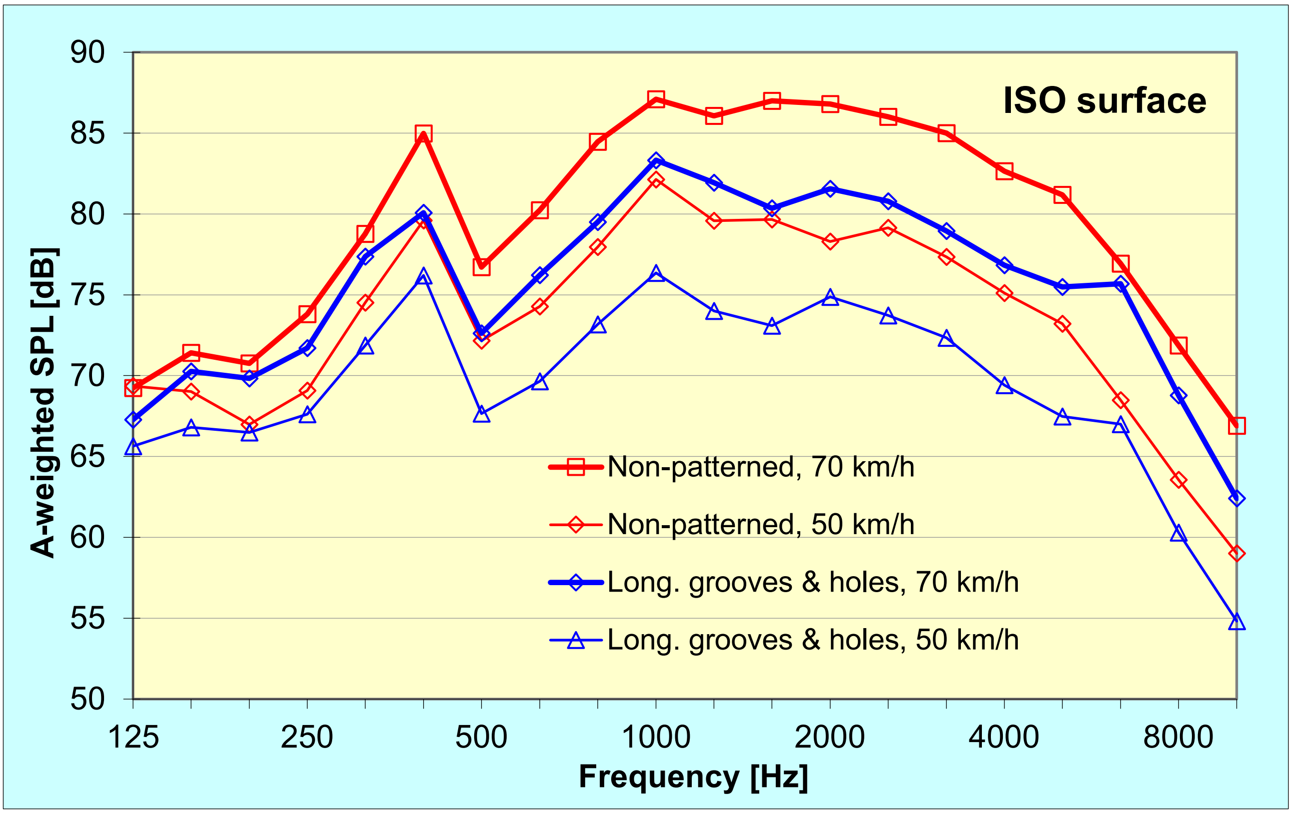

Figure 7: Frequency spectra for two Composite Wheel prototypes at 50 and 70 km/h, measured in 2007 with the drum method on an ISO replica surface. The two prototypes are one with a non-patterned but full tread; the other one having a similar tread but with three longitudinal grooves and with holes drilled through the rubber and belt.

Finally, it should be mentioned that an analysis of the optimum size and spacing of holes in the Composite Wheel, arrived at the conclusion: "Looking at the sound radiation from vibrations, it is not possible to find an optimum hole size for the whole frequency range. The calculation shows that the larger the holes, the smaller the radiated power. However, in a narrower frequency range, the size of the holes can be optimized. In the frequency range between 800 Hz and 1 kHz, the optimum hole size was calculated to about 6 cm when 9 equally spaced holes were used around the wheel circumference" [8].

It follows that the holes in the Composite Wheel were far from optimized.

7. DISCUSSION AND CONCLUSIONS

In a multi-national project conducted in 2002-2008 the concept of airless tire named Composite Wheel was developed and tested. In this paper, the noise generation mechanisms which potentially cause the noise reduction of such airless tires compared to air-inflated tires are analyzed and discussed in detail, based on the special features of airless tires. The discussion is especially looking at how the findings can be up-scaled to the airless truck tire for which prototypes are being developed in project LEON-T.

It is concluded that the reasons for the airless tires of these concepts being so much quieter are the openness of the entire tire-wheel system. There is no enclosed box that can enhance the bass radiation as for the air-filled torus of conventional tires and the tread and belt itself can be perforated to reduce or almost eliminate the air pressure build-up due to air pumping. The "acoustically transparent" tread and belt also helps reducing radiation of low and middle-range frequencies from vibrational mechanisms as the "baffle" provided by the tread/belt is perforated. Quite unexpected, there are no signs of the "spoke impact" mechanism, which should have appeared as a peak in the frequency spectra proportional to the speed. The reasons are probably that the spokes are attached to the belt in an appropriate way combined with the acoustically transparent tread and belt which reduces the acoustic radiation efficiency.

The paper shows measurement results from the earlier project which illustrate both the general noise reduction by the Composite Wheel compared to a reference air-inflated tire over most of the frequency range, and the effect of opening up a slick tire tread with longitudinal grooves which are perforated with holes. This shows that a slick (non-patterned) tire is not at all the quietest tire available.

However, there are also problems with our airless tire concepts. A structural resonance appearing around 400 Hz in the Composite Wheel is prominent and reduces the A-weighted overall noise reduction substantially: especially at lower speeds. There are also signs of some other structural resonances at 1000 Hz and possibly also at 2000 Hz. Finally, it is suggested that the pipe half-wavelength resonance created in the grooves between each pair of holes is the reason for the peak in the spectra in the 6.3 kHz band.

It should be possible to reduce the structural resonances if one can identify how they are caused, in which case both exterior and interior noise emission will be reduced. By an optimized "perforation" of the tread and belt structure, the Composite Wheel could be made almost totally "acoustically transparent"; which should reduce both the air pumping and the amplifying horn effect to a negligible level. The 400 Hz structural resonance could probably be reduced by cutting some openings in the rim. However, all cuts and perforations have a cost in terms of reduced mechanical strength which must be observed.

Projecting the results discussed above to the LEON-T airless tire, it is evident that perforations in the tread and belt will be important. They should be as large as is acceptable without jeopardizing the mechanical strength. A tread pattern with longitudinal grooves, with holes in the bottom is adequate (for the trailer and steering axle prototype); however further refinement with optimized rubber compounds and sipings would help reduce the noise. The latter was never done in the Composite Wheel project; yet the performance was good. It is expected that the rubber compound and sipings will be important to reduce the stick-slip noise generation mechanism, as well as rolling resistance.

The open space between the spokes will be effective in reducing any “baffle” effect in the spoke region, but the rim area may be a challenge. The rim (as well as the tread/belt) could constitute a “sounding board” which is excited by the resonant vibrations in the spokes. Therefore, the rim must be very stiff and if it could have some perforations, it should be an advantage. However, it is not easy to see how that can be achieved.

Finally, in the design shown in Figure 3, the spoke impact mechanism may be much more significant than in the Composite Wheel as there will be greater distance between the spokes where the impedance on the tread/belt system will be much lower than on the top of the spokes. The connection between spokes and belt will be very important to reduce this problem. This connection is also critical from the durability point of view as large strains will occur in these contact points.

Overall, the challenge with the airless tires in LEON-T is not only to produce a product that will work well from durability and safety points of views, but also to achieve the target of 6 dB noise reduction compared to today’s air-inflated tires. The year ahead will be exciting.

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The author also wants to recognize the cooperation in the earlier Composite Wheel project with Mr Hans-Erik Hansson for his invention and production of the Composite Wheel prototypes as well as Prof Jerzy A. Ejsmont at the Technical University of Gdansk (TUG) who made the noise measurements on the TUG drum facility.

Furthermore, in the LEON-T project, especially the cooperation with Dr Bharath Ananthara-maiah at Applus+ Idiada in Spain, Mr Hans-Erik Hansson at Euroturbine AB and Dr Linus Fagerberg at Lightness by Design AB, the latter two in Sweden, shall be recognized. However, for the noise analyses and discussions in this paper only the author is responsible.

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