What Powertrains Could learn from Each Other

Thinking outside the box

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Introduction

The discussion concerning electrification of vehicle powertrains has caused an abrupt rise in the number of potential drive concepts. In the past, the question revolved around whether a diesel or petrol engine, an automatic or manual transmission was the right choice; today's offerings include a huge variety of new architectures, with an electric motor added to the combustion engine or used as a single drive.

Most of the concepts are supported by the tangible benefits of the respective model. Certain arrangements and combinations seem to be beneficial depending on the weight given to advantages and disadvantages. This places significant additional burden on automotive manufacturers and developers as a mainstream has yet to emerge.

This article cannot and will not clarify this issue. Rather, its aim is to solidify interesting individual aspects of the various powertrain concepts on offer and to consider how a property of this kind can be transferred to a completely different drive. Viewed in this light, this approach has much in common with genetic engineering, which is based on removing individual genes from a living being and then inserting them into another. The procedure is based on the understanding that all species ultimately have genomes with similar structures. Similarities can also be seen in technical products, even if they are based on different technologies. When we get down to the basics, we realise that all products are based on a few physical principles.

The laws of conservation for energy, momentum and charge lead to a far-reaching analogy between mechanics and electrics. This analogy is presented

in the first section and then the analogy principle is expanded. The aim is to transfer certain objectives, thought processes or procedures to other technologies. What new findings, perspectives and ideas may we discover? These are presented in the following using examples.

Mechanics and electrics – are they really two different worlds?

Literature on physics or the engineering sciences contains a great many analogy analyses between mechanics, electrics, acoustics and hydraulics. In this article, we are restricting ourselves to electric and mechanical correlations and are using the physical laws of conservation as the basis. We will then draw up parallels between the disciplines. In addition to the key laws of conservation, we will be using the first law of thermodynamics along with the law of conservation of momentum in mechanics and charge in electrics.

Based on these two physical variables, the total of which always remain constant (an experiment you may also want to conduct), it is feasible to view momentum and charge as analogous to one another. It follows directly that their time derivatives also correspond: Force ($F = \frac{dI}{dt}$) and current ($I = \frac{dQ}{dt}$). By gradually expanding this analysis, it is also possible to establish analogies for other mechanical and electrical variables [1] (Table 1).

From this, it follows that accelerating a mass corresponds to charging a capacitor (Figure 1).

Mechanics	Electrics
Energy	Energy
Power P	Power P
Impuls I	Charge Q
Force $F = \frac{dl}{dt}$	Current $I = \frac{dQ}{dt}$
Speed v	Electrical Potential U
Mass m	Capacitor C
Spring	Solenoid
Reciprocal spring constant $\frac{1}{D}$	Inductivity L
Damper	Resistor
Mechanical resistor	Electrical resistor
Viscosity	Electrical conductivity

Table 1 One of the possible analogies between mechanical and electrical variables. This example uses an accurate circuit analogy based on the laws of conservation of momentum and charge

If we look at electrical oscillating circuits, the same analogous mechanical transducers can be obtained by replacing the capacitors with mass, coils with springs and electrical with mechanical resistance. If this approach is taken, these analogous systems can then be described using analogous equations.

Unfortunately, mechanical and electrical engineering were developed at different times and by different scientists, which is why individual variables have different names. This makes it difficult to spot analogies in the equations at first glance.

Of course, the exact analogy also has its limits, namely when certain physical conditions differ from each other. On account of this naming convention, correlations for the acoustic and optical Doppler effect are not exactly the same; this is be-

Figure 1 Analogy of mechanical and electrical oscillating circuit

Figure 2 A comparison can be drawn between a speaker and an antenna. Both emit output in the form of waves

cause acoustic waves are bound to the media, while electromagnetic waves are not. The laws of relativity apply to the latter with a speed of light that is the same for all observers, regardless of their speed. This restriction does not apply to a “mechanical” sound wave observer.

Figures 2 and 3 show further examples of analogies. Speakers and antennas cor-

respond directly. Transformers find an analogy in a pulley or gearbox.

A transformer converts electrical energy within the energy form so that the product comprising voltage and electrical current remains constant. For a pulley, force and travel are analogous, whilst for a transmission the variables are torque and rotation angle.

On the electrical side, the group of transformers also includes converters, inverters and power converters in general terms. Strictly speaking, these devices perform the same task as a transformer. They convert voltage and current into a different voltage, while taking the law of conservation of energy into account.

This last example in particular shows that an analogy can also be understood in a wider sense when the components cannot be accurately described using the same physical, basic equations. The crucial aspect for this kind of extended analogy is to use the same or at least a similar physical fundamental idea. The following example does just that.

Figure 3 A direct comparison can be drawn between the transformer and a pulley or a gearbox when rotation is involved. This group of transformers also includes converters, inverters and power converters.

Electric gearbox or mechanical transformer?

An initial comparison of combustion engines and electric drives shows that, in addition to a clutch, the combustion engine needs a shiftable gearbox with a lot of gears as a start-up device, while the electric motor can cope without any of these elements.

The combustion engine therefore requires multi-gear gearboxes with the largest possible spread angle, as an optimum combustion process is only possible within certain operating ranges. In order to get as close to this optimum point at any driv-

Figure 4 The motor characteristics are compiled into an overall characteristic curve comprising the different gear stages. This overall characteristic curve has a similar shape to that of an electric motor.

ing speed and load, the number of mechanical gears used has seen a steady increase over recent decades. Individual engine characteristic curves make up an overall characteristic curve (as shown in Figure 4), which is already familiar from electric motors.

Why does the electric motor apparently not need a gearbox to create a characteristic curve? Quite simply because the gearbox is concealed in a completely different place under a false name.

Figure 5 shows a diagram of the powertrain with a combustion engine. Chemical

energy is fed in and converted into mechanical energy in the engine. As it is preferable for this process to take place at a certain operating point, a downstream gearbox converts speed and torque as is currently required by the drive (whilst following the law of conservation of energy).

The functional chain for electric motors is slightly different. Supplied electric energy is converted in an electronic power unit (sometimes also called electric energy converter, frequency converter or inverter) so that the electric motor can provide the torque and engine speed required for output. The difference between combustion engine and electric motor drives is therefore that one has an electric “gearbox” before the actual motor and the other has a “mechanical” transformer after the actual engine.

This is especially clear when we consider electric recuperation. The electric motor acts as a generator to produce a voltage proportional to the speed. This must then be transformed into battery voltage via the electronic power unit.

Incidentally, this was not always the case. Before the advent of modern electronic power units, electric motors were designed with even narrower operating ranges, as is the case with combustion engines. Therefore, all kinds of variable gearboxes were available back then.

Figure 5 Functional chain for combustion engine powertrains and electromotive powertrains

These included continuously variable gearboxes with which the fixed speed of an electric motor could be adapted to meet the power output requirements (bottom image). Think of it like this: The converter only moved upstream from the actual power generator at a very late stage in the development of the electric motor.

Could the combustion engine also make a similar development? In theory, yes, if the chemical energy was already converted. One possibility would be to change the chemical composition, according to the current power requirement. For example, the oxygen content could be increased up to the point of combustion with pure oxygen, even if this suggestion appears somewhat impractical. To do this, it would probably also be necessary to modify the fuel. For high power requirements, fuel with a higher energy content could be injected. Of course, all components would then need to be designed to cope with much higher combustion pressures. But this is precisely the way in which the electric motor changed when the converter moved upstream from the engine. Each and every component had to bear increased torques and forces.

Can an electric motor produce a Miller cycle?

In combustion engines, the aim is to utilise chemical energy to optimum effect by increasing the work area, i.e. the stroke. Figure 6 shows the Otto cycle. It is immediately apparent how much additional energy could be obtained if expansion were to be extended. The same applies to a higher compression ratio. In both cases,

Figure 6 The Otto cycle. Yield can be increased by extended compression and expansion

the area between the curves, representing the usable work area, is considerably increased. Deliberations of this kind concerning combustion engines are associated with the well-known names of Atkinson and Miller.

How can this idea be transferred to the electric motor? Could the electric motor also produce a Miller cycle? Is there something similar to a higher “compression ratio” or an extended “stroke”?

Figure 7 shows the basic principle of electromagnetic attraction, which ultimately describes how all electric motors work.

A magnetic field is generated by a current; this field attracts the armature. During this attraction, the force increases as the interval or air gap becomes smaller. Halving the air gap results in a force four times as large. The mechanical energy generated is equivalent to the area between this force characteristic and the reference line. This diagram is not associated with a famous name such as the Otto cycle, but it is a direct analogy.

Based on this finding, the aim is to keep the air gap in electric motors as small as possible; however, there are limits in terms of design. This is also the case

Figure 7 The attractive force of an armature in a magnetic circuit

for the “extended” stroke, which would require a larger distance between the poles to implement increased attraction travel. Is there a way of breaking through these limits?

One approach may be the roller motor. Figure 8 shows the basic structure. A rotor made from magnetic material rolls around within a stator. The air gap can thus be reduced to zero [2]. The extended stroke is generated from the difference in diameter between the rotor and the stator, and this determines the maximum air gap.

Enhanced utilization solely of the magnetic attraction characteristic is not sufficient. It must also be ensured that the characteristic curve is traversed as often as possible; this requirement is not yet ful-

filled. This is because each stator electromagnet would only create one attractive force per complete rotation. On a standard electric motor, this happens multiple times according to the number of pairs of rotor poles. The rotor needs to roll correspondingly faster in order to mitigate this disadvantage. This should not cause any major difficulties, as the rotor only experiences a very small amount of rotation as it rolls. This rotation is taken off the central shaft with a further high gear reduction ratio. All in all, these actions create a motor that delivers high torque at low power-take off speed. Initial interpretations show that, in theory, this concept allows a higher weight to power ratio to be achieved than a permanently excited synchronous motor. This may be an ideal concept for wheel hub motors. However, until we reach that point, many details still need to be resolved, such as durable materials for the guide rails and unbalance compensation. And we may find that this process is also given a similarly pleasing name such as Carnot, Miller or Atkinson.

Figure 8 The roller motor. An eccentric rotor rolls around the internal diameter of the stator

Irregularity — an inevitable fate of combustion engines?

The irregularity of the crankshaft speed seems inextricably linked to the combustion engine principle. For this reason, downstream measures to reduce this irregularity are needed for each combustion engine to prevent gear rattles, humming noises or even rigidity problems. Many of these options were presented at the Symposium.

The phrase “Runs like an electric motor” is often used in technical jargon to describe a measure that is particularly effective. Why does a combustion engine have irregularities and an electric motor does not? What are the differences and what principles are responsible for these?

First off, we once again return to the number of cylinders, or better put: The number of power deliveries per revolution. In case of four-cylinder engines, there are only two of these power deliveries, which are called ignition in combustion engines. There is an extended pause between each of these ignitions. So it is no wonder that a crankshaft cannot rotate evenly if a short but sharp torque shock occurs only twice per revolution. This is not the case with the electric motor, in which each stator coil is responsible for power delivery. Looked at this way, an electric motor actually has many cylinders, while the combustion engine has a reduced number of cylinders for well-known reasons. So it is only natural that we see differences when we compare a three-cylinder combustion engine with a “twelve-cylinder” electric motor. However, the irregularity of the combustion engine is also so great because compression takes place prior to

every ignition and slows down the crankshaft. This may sound like a disadvantage at first, but it is immensely important for subsequent ignition. The principle that can be derived from this is: Sacrifice first so that a particularly high yield can be achieved during the next cycle.

This principle is to be found in many areas. As man progressed from hunter and gatherer to farmer, he realised precisely this principle. The best crop was taken from the harvest to be subsequently used as seed.

Taking something of value out of circulation and using it profitably to bring in a particularly large harvest at the end of the process always indicates a progressive level of development. The combustion engine has already scaled these heights, but this principle is not used in the electric motor.

In electric motors, the permanent magnets or mechanical resistance poles could be briefly attracted inwards by applying energy to then have a particularly long working

Figure 9 Preventing roll moments by means of a secondary shaft designed to absorb the opposing angular momentum of the crankshaft

stroke during magnetic attraction. This would also recuperate many times more energy than the previous energy consumption. A theoretical example for which constructive ideas have yet to be developed. In any case, the electric motor could learn from the combustion engine when it comes to this principle.

Let's look at irregularity again: It appears to be inextricably linked to the combustion engine. We should not just consider the crankshaft in this regard, but also the engine block, which must also absorb the reactive forces according to the law of physics "every action has an equal and opposite reaction". The question we are faced with is whether there is a standard way of combating this irregularity?

For the engine block at least, the bibliography [3] contains the description of a procedure for eliminating retroactive effects by means of alternating roll moment. It suggests providing an additional shaft driven by a set of spur gears which is not unbalanced in contrast to standard balancer shafts (Figure 9).

By using this arrangement, it is possible to completely eliminate all roll moments regardless of frequency or order, if the following condition is met:

$$J_{\text{crankshaft}} = i \cdot J_{\text{secondary shaft}}$$

The derivation is very simple if we start from the law of conservation of angular momentum. Subsequently, the total of all torques before and after ignition must be the same. This kind of ignition accelerates the crankshaft; it therefore receives additional angular momentum. For this reason, the engine block must absorb the opposing angular momentum to ensure that the law of conservation of angular momentum is fulfilled.

The balancer shaft shown in Figure 10 rotates in the opposite direction and generates momentum with opposite signs. The

Figure 10 14-cylinder double star rotary engine, Gnome design from 1916 [4]

angular momentum of the crankshaft and balancer shaft caused by ignition can be cancelled by selecting an appropriate transmission ratio and mass moment of inertia. This leads us to a somewhat surprising finding, which is that no angular momentum remains for the engine block. The engine block is therefore not affected, at least as far as roll moment is concerned. This applies to all orders.

According to the principle "every action has an equal and opposite reaction", it is also possible to operate the engine the other way around: The crankshaft is fixed and the engine block rotates. This kind of rotary motor was the predominant engine design used for aeroplanes until the end of the First World War. If this type of engine were also to be fitted with the balancer shaft described above, the entire irregularity could be eliminated at the power take-off, completely irrespective of the excitation frequency or order. Presumably, the pressure of irregularity will not become so great that a rotary engine would seriously be considered. It is nevertheless an interesting idea; in principle, it

would be possible to completely eliminate irregularity at the power take-off, but at the price of extremely high mass moment of inertia.

A quite different conclusion can be drawn from these analyses. If an inversely rotating mass reduces the engine block's rolling oscillations, then these are actually enhanced by the auxiliary rotating equipment rotating in the same direction. This is indeed the case if crankshaft irregularity transfers to the auxiliary equipment, i.e. if no isolation is provided by a vibration-isolating belt pulley or an alternator freewheel pulley. Reversing the auxiliary equipment direction of rotation would cause a tangible reduction in roll moment (Figure 11).

Just changing the direction of rotation alone would approximately halve the roll moment. Looking at an auxiliary drive (Figure 12) shows that only the virtually massless deflection rollers in today's drives have this reverse direction of rotation. If more powerful alternators designed to perform starting and certain hybrid functions, are used in the future, it could be possible to fully compensate the roll moment thanks to

Figure 11 Effect of reversing the auxiliary equipment direction of rotation on an engine block's roll moment

Figure 12 In the case of a conventional front end accessory drive, all units have the same direction of rotation as the crankshaft

the associated higher mass moment of inertia. For this to happen, solutions for reversing the direction of rotation would need to be found.

The centrifugal pendulum-type absorber – a quite different prospect

Progress made in the field of centrifugal pendulum-type absorbers has essentially been achieved thanks to modern simulation methods. These simulation possibilities were not around when the first work was conducted in this area about 80 years ago. Therefore, the aim was to develop analytical solutions for less complex systems, and these studies led to surprising results at the time. Depending on the precise order it is aligned to, the centrifugal pendulum-type absorber is, in fact, an effective secondary spring mass that is the result of the equation

$$J_{\text{secondary}} = \frac{m q_p^2 (L+I)}{(q_p^2 - q_e^2)} \quad [5].$$

Here, m is the mass of the pendulum, L the radius of the suspended pendulum, l the effective pendulum length, q_p the aligned pendulum order and q_e the excitation order.

The equation proves that this effective secondary spring mass can take surprising values. If $q_p = q_e$, an infinite secondary spring mass moment of inertia is generated for this order under the condition that the vibration angles are not limited, which is obviously not the case in practice. This is aimed for in normal designs. Therefore, the order can be entirely cancelled at the point at which the centrifugal pendulum-type absorber is attached. The pendulum really does act like an infinitely large mass.

If q_p is greater than q_e , smaller values are produced for the secondary moment of inertia.

It is interesting and at first difficult to imagine a case in which the calibration order q_p is slightly smaller than the excitation order q_e . This produces negative secondary moments of inertia. If the calibration is selected so that $J_{\text{secondary}}$ equates directly to the negative value of the mass to which the pendulum is attached, the total mass of the order in question disappears completely. So, the mass moment of inertia for the order in question can be eliminated completely using the oscillation equation for a simple transducer.

This is a surprising result. A relevant variable can simply be eliminated from a fundamental physical relationship. Two issues are raised: Firstly, are effects of this kind that can make crucial variables disappear from fundamental equations also present in other areas of mechanics or electrics? Even if no answer has yet been found to this question, it is suspected that these types of cases could exist.

The second question is whether this effect can be used in practical terms. A negatively calibrated centrifugal pendulum-type absorber could be positioned on

Figure 13 For the second order, the mass moment of inertia of the generator is eliminated by a centrifugal pendulum-type absorber with a slightly negative alignment

the alternator in the belt drive, and the alternator mass moment of inertia could be completely eliminated for the second order. The belt drive would then see no alternating forces at all for the second order, just as if the alternator mass moment of inertia had disappeared. This is not just theory; the simulations in Figure 13 demonstrate this disappearing mass moment of inertia.

In this case, the state could actually be achieved by appropriate calibration, with the alternator oscillating precisely in the same second order as the crankshaft, but with extremely small belt forces.

The range trick

Combustion engines today are clearly ahead of the pack when it comes to range. At present, batteries cannot even begin to store the energy as we are used to with fuels. However, this advantage can be considered from a somewhat different perspective.

Figure 14 shows the reaction equation of hydrocarbon with atmospheric oxygen and the associated weight ratios of the reactants. Burning 50 kg of petrol in the engine requires the oxygen contained in approximately three quarters of a tonne of air. This produces 155 kg CO₂ (i.e. around three times as much as the fuel weighs) and a relatively small amount of water.

The fuel's supposedly high energy density is therefore due to the fact that the heavier reactant is simply obtained from the ambient air. A moon vehicle would need to carry approx. 160 kg pure oxygen for the 50 kg petrol to provide the necessary volume of reactants.

Could the environment also be a factor for batteries?

The answer is clearly: Yes. Zinc-air batteries, such as those used for hearing aids, have already proven this is the case. Although they are (not yet) rechargeable, they take the oxygen needed for the electrochemical reaction or oxidation from the air.

Zinc-air batteries thus have the highest energy densities of any battery available today.

Intensive work is underway on lithium-air batteries, which promise the highest energy densities. Lithium is oxidised to lithium peroxide Li₂O₂ in these batteries. During this process, each lithium atom gives off an electron at a voltage of approx. 3 V. The resulting energy content needed for a distance of 1,000 km is shown in Figure 15.

The example considers a vehicle that consumes 5 l petrol over 100 km. 50 l petrol are then needed to travel 1,000 km. This corresponds to approximately 38 kg petrol with a fuel value of 450 kWh. At an efficiency of 22 %, approx. 100 kWh are then applied to the wheel as mechanical work, which is exactly what is required to travel 1,000 km.

Assuming that an electric vehicle needs just as much power for the drive, we can calculate the required energy that must be stored in the battery. We estimate an efficiency of 80 % for the electric motor and battery discharge. Values of this magnitude seem to be achievable. In this case, 125 kWh energy would be necessary and would

Figure 14 Reaction equation for combustion of a typical hydrocarbon, such as is contained in fuels

Figure 15 Energy consumption for 1,000 km

need to be stored in the battery. To obtain this electrical energy, we would only need to oxidise approx. 10.5 kg lithium to Li₂O₂ (lithium peroxide). This small amount is surprising at first, but can be verified by another method. If each lithium atom gives off an electron with a voltage of approx. 3 V, the calculation results in the same small amount of required lithium, which then reacts to 25 kg Li₂O₂. Quite manageable quantities and weights.

This is from the view of pure theoretical chemistry and physics, which shows us that batteries with extremely high ranges may be possible in the future, as long as the charge process can work in reverse. The big issue is the amount of infrastructure needed to implement a functional battery. This includes housing, cooling, power supply lines, monitoring and electrodes, to name just a few. However, it should not be forgotten that even combustion engines need additional components, such as tanks, fuel pumps, catalytic converters, etc.

Of course, these considerations do not prove that high-performance and affordable batteries will be available within the next few decades. On the other hand, experience gained from the history of technology and physics show that virtually everything not explicitly ruled out by natural laws, has been achieved with reasonable levels of effort and expense.

Oxidation or electric mobility from a different perspective

What actually happens during combustion or oxidation? Put simple, it can be described as we were taught in chemistry lessons. The oxygen prizes electrons from the hydrogen and carbon, and through this process becomes a negatively charged particle. This transition of electrons releases the same energy that is normally referred to as heat value or energy content for combustibles and fuels. This means a current is flowing, even if only at an atomic level. In this sense, combustion is already an electrochemical process, meaning we are closer to electric mobility than many think. However, the flow of electrons is not used directly as electric current. Only cold combustion fuel cells make use of this knowledge.

In combustion engines, the energy released by the flow of electrons is converted into heat, which expands the combustion gases and performs work. This is similar to a battery whose electrical energy is initially converted into heat by an immersion heater (Figure 16) in order to subsequently op-

Figure 16 Electric power causes gas to expand which can then perform work

erate a steam engine using the steam. It is precisely this intermediate step of heating that results in the poor efficiency of combustion engines.

Summary

In this article, we have considered and analysed a series of analogies. As has been demonstrated, these analogies result in a varied mixture of interesting, unexpected, partially useful and sometimes curious findings. However, thinking in analogies always inspires engineers and thus potentially triggers thought processes that bring about completely new and creative concepts.

The article has only presented a small selection of possible analyses of analogies. There is a whole set of further questions that could be posed. Such as:

Is there an electrical equivalent to the turbocharger that recovers at least a part of the lost energy?

What is analogous to the catalytic converter or to exhaust gas recirculation? Can

electric motors also feature cylinder deactivation?

In modern electric motors, a magnetic reluctance ratio is used in addition to the permanent magnets. The reluctance ratio is based on completely different physical principles. Is there an analogy for this in other engines?

This is only a small selection of other potential questions. Some issues could not be covered within the confines of this article, while for others no analogy at all was determined. It may be that no analogy exists in certain cases. But searching for these parallels always produces food for thought and provides the opportunity to devise new solutions.

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