TRANSMISSION DESIGN FOR VERY HIGH INPUT SPEEDS

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ABSTRACT

When driven by conventional power sources, the input shafts of most transmissions rotate at speeds below 10,000rpm. To improve efficiency the electric motor designer is increasing the speed of its rotation and currently speeds in the region of 20,000 rpm are becoming common place.

Changing the speed has moved the operational window significantly outside the specification of many common components used in volume production of geared power transmission systems such as seals and bearings. Specialist solutions are already available but typically come at a cost that could prohibit their use as electric and hybrid vehicle technology penetrates larger volume markets.

There are further considerations at a system level such as the need for additional meshes. Transmission lubrication regimes are particularly sensitive to rotational speed; this presents some significant challenges with regard to maintaining lubrication in critical areas. Furthermore, energy losses at the input shaft due to drag and churning become much more significant with a high speed, low torque system. Each component also has to be designed to withstand far greater centrifugal forces.

INTRODUCTION

This paper presents solutions to these problems, and how carefully designed alternatives to common systems facilitate the smooth introduction of transmissions for high speed motors into larger volume production in a cost effective manner. Considerations are also made for the system performance and how the system designer can ensure that the electric motor is protected against loads generated in the transmission.

THE NEED FOR HIGH SPEED TRANSMISSIONS

There is an increasing focus in the automotive industry on the development of hybrid and electric vehicles. Since mass production hybrid vehicles became available in the late 1990’s the level of hybridization has continued to rise steadily. The first generation Toyota Prius had 30kW of electric power when introduced in 1997. This increased to 33kW in 2001, then to 50kW in 2004, and up to 60kW in 2010. During this development the motor mass has actually reduced resulting in the current motor power density being four times that of the first generation.

As motor technology has developed, and supported by the developments in battery technology, pure electric vehicles have become a mass production reality. Electric vehicles have traditionally struggled to match the vehicle performance expectations of consumers however, and this coupled with concerns such as vehicle range and recharging times have impacted sales.

Electric motor power density is therefore a key factor in the development of hybrid and electric vehicles for the modern automotive market. Integration of the electric motor and transmission can assist in a number of areas. Reducing interfaces between discrete components and designing the powertrains as a single system can reduce the numbers of components such as bearings, and minimize the size of other components such as casings by ensuring elements serve multiple functions.

The ultimate purpose of a transmission is the conversion of speed and torque. As electric motors have developed, their output speeds have tended to rise due to the relationship between motor mass and torque. As motor mass has a direct influence on motor cost, for more powerful motors to continue to be cost effective their output speed must rise. This generates further challenges for the transmission in terms of increased ratios and higher surface velocities. It is generally agreed however that overcoming these transmission challenges is more cost effective than increasing motor weight.

SYSTEM LEVEL CHALLENGES

The primary concern for any engineer tasked with overcoming these challenges is the selection of a suitable transmission arrangement. This is not a simple task however and must consider all of the individual component concerns that will arise from any given arrangement. A key factor in this selection is the overall ratio that must be achieved, based upon the motor performance and vehicle requirements. Packaging and driveline arrangement are also likely to have a significant influence on the arrangement but even within a defined package envelope there are likely to be number of solutions that must be considered and the appropriate solution selected.

To utilize the increase in input speed, the overall transmission ratio will need to be greater than a conventional transmission for this application. This may necessitate a shift away from the typical arrangement of a two stage parallel shaft transmission.

Whilst parallel gear sets are generally considered to have greater mechanical efficiency, epicyclic gear sets are capable of greater ratio steps in a single stage. This can have the advantage of reducing the number of stages required between the motor and the wheel, but also means that the high speeds can be reduced as soon as possible. Epicyclics do however generate their own challenges in the form of component accuracies required, planet bearing durability, and managing unequal planet loading. The quantity and quality of the components required can also increase costs.

The overall ratio that is achievable with a conventional two stage parallel axis transmission is limited due to the tooth geometries required whilst maintaining sufficient strength and durability. At ratios approaching 4:1 the gear geometry can become prohibitive due to the small module required to maintain a sufficient number of pinion teeth in order to avoid manufacturing issues such as under cutting and maintaining tip width. In addition the packaging of the large wheel tip diameter can become problematic.

Whilst a two stage parallel axis transmission may struggle to achieve the ratios required to maintain axle torque with a low torque, high speed motor, a three stage parallel axis transmission would be more than capable. Direction of rotation of the input tends to be insignificant to electric driven vehicles as reverse is generally achieved by counter rotation of the motor. Integration of a high speed motor into a hybrid powertrain may be more constrained in this respect as the internal combustion engine must still be accounted for. Ratio split is unlikely to be evenly distributed in such a transmission and packaging and durability targets are likely to limit the ratio closest to the input. This may result in high peripheral gear speeds needing to be considered at an early stage of the design.

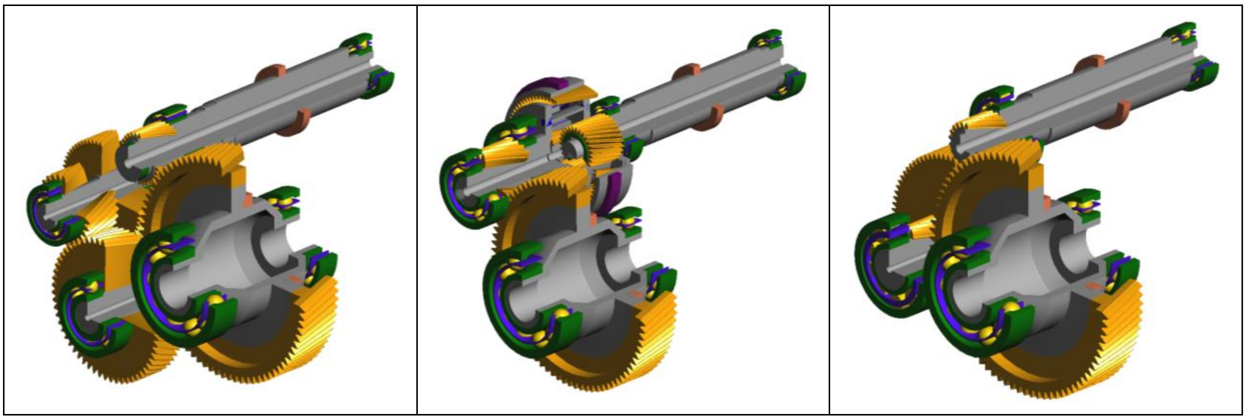

Figure 1 – High Input Speed Transmission Concepts

Helical gears are the default choice for parallel axis and epicyclic transmissions in the automotive industry, even more so for electric vehicles due to their superior NVH performance required in lieu of an internal combustion engine to mask even minor NVH issues. Whilst their increased contact ratio assists with the reduction of transmission error, the axial loads and moments due to the helix angle must be supported by the rest of the transmission in addition to the radial separating loads. Rolling element bearing load capacity generally increases with diameter however their speed capacity reduces with diameter also. The supporting elements within the transmission must therefore be considered at a conceptual stage.

Transmission efficiency targets are of great importance, particularly for electric vehicles as it translates directly to vehicle range. The ability to analyse the power losses of the various components at a range of speeds and loads at a conceptual stage is essential to ensure that these targets are met. For the three concepts considered above, an efficiency delta of over 0.5% has been calculated considering the gear and bearing losses alone. Power loss at cruising speed is often a more important figure than efficiency in such applications. In this respect the two stage concept out performs the others by between 50 W and 100 W at cruising speed and loads equating to 30 mph, 50 mph, and 70 mph.

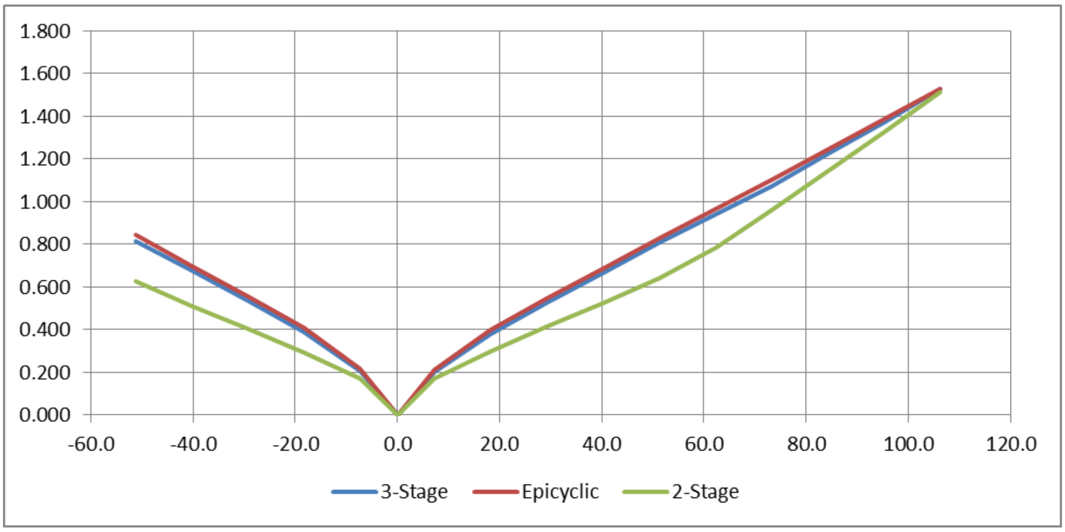

Figure 2 – Transmission Power Loss at 7000 rpm Input Speed

Lubrication of the necessary transmission components must also be accounted for in the transmission arrangement. Higher input speeds can present issues for lubrication as centrifugal forces make it increasingly difficult to manage oils and present sufficient quantities at the required locations. Gear meshes with high pitch-line velocities can be particularly problematic to lubricate adequately without the use of forced lubrication systems. A forced lubrication system creates additional losses within a transmission reducing efficiency, a significant performance target for modern transmissions. Equally, high gear pitch line velocities passing through a body of oil can create significant losses as the drag torque is approximately proportional to the square of the pitch line velocity. These losses must be accounted for in the early stages of the transmission conception to ensure that the most efficient system is selected.

A high input speed transmission has the potential to generate greater amounts of heat due to increased velocities where sliding contact occurs. These interfaces must obviously be designed very carefully to minimize the heat generated, and if possible avoided in the first place. Sliding contact is unavoidable in an involute gear mesh however and the heat generated will need to be dissipated. The lubricant must remove a certain amount of the heat from the mesh and transfer it to the casing, for subsequent dissipation to the environment. The amount of heat the casing is able to dissipate must be balanced with the heat generated to ensure the transmission temperature does not increase to levels beyond the capabilities of the components contained within, including the oil. The oil must also be capable of withstanding the high sliding velocities and associated shearing without degrading excessively over the vehicle life.

DESIGN SOLUTIONS

GEAR DESIGN

An additional risk to gears in a high speed transmission is scuffing failure. Gear scuffing occurs when the lubrication film between the two gear flanks breaks down. When this occurs the tooth surfaces instantaneously weld together and are then pulled apart due to the combined sliding and rolling action of the tooth contact. Transmission lubricants often include additives packages to try and prevent this by enabling the oil to cope with the extreme pressures generated. However these additives are generally sulphur and phosphorous based increasing the environmental impact and complicating the handling of the oil.

The breakdown of the lubricant film is due to the friction generated at the gear mesh. At the pitch point the two tooth flanks roll against each other. Away from this point however the two surfaces begin to slide against each other as well. This sliding velocity increases with distance away from the pitch point. The contact pressure also varies depending on the number of teeth in contact and the position of the contact point on the tooth flank.

The gear macro geometry can be designed to minimize the sliding by reducing the height of the gear tooth either by using a smaller module, or by reducing the addendum and dedendum of the tooth form. These changes will both have an impact on the strength of the gear teeth however and the magnitude of the changes is likely to be limited by the duty cycle that the gears are required to endure. A shorter gear tooth also has in increased stiffness making it more sensitive to geometry errors. Additional changes to other gear geometry parameters will be required to recover the gear contact and bending strength.

A number of standards exist for the analysis of scuffing risk however their application is complicated by the effect of gear micro-geometry. These flank corrections, along with the elastic deflections of the gear teeth, can have a significant impact on the contact pressures within the gear mesh. The accurate modelling of the gear tooth contact is therefore important to correctly define the flank corrections and minimize the risk of scuffing occurring. The correct application of tip relief to both of the gears can be used to reduce the contact pressure as the sliding velocity increases, minimizing the peak in frictional force.

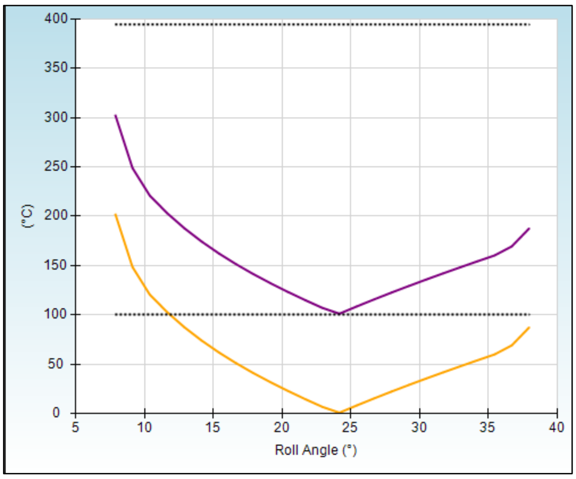

Figure 3 – Lubricant Flash Temperture without Micro-Geometry

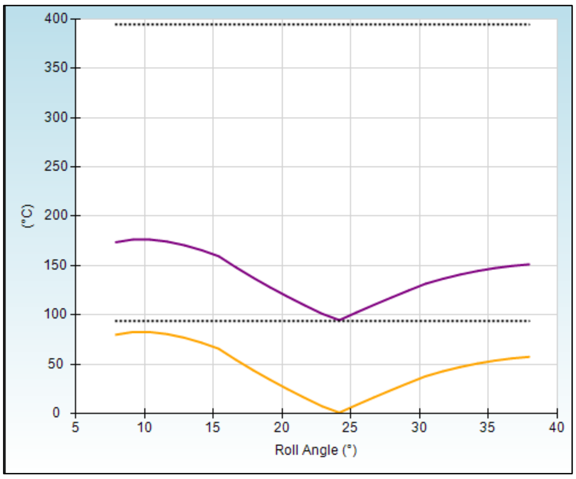

Figure 4 – Lubricant Flash Temperature with Micro Geometry

A further reduction in scuffing risk can be achieved by reducing the coefficient of friction at the gear tooth contact. This may be by an improvement in the surface finish of the gear flanks or the addition of a low friction coating to the components. Processes such as super finishing have been shown to have a noticeable effect on the contact durability of gears. Certain coating technologies have also been successfully applied in other applications to reduce gear mesh friction. Both solutions however are additional to the existing manufacturing process and as such the increase in component cost can be significant.

The careful application of the above gear design recommendations will also have an additional benefit to the transmission, an increase in efficiency. The friction that is generated in the gear mesh is energy lost as heat. Increasing the efficiency of the gear mesh also reduces the requirements on the transmission lubricant and lubrication system to collect and dissipate heat.

Noise has become a significant factor for electric vehicle transmissions. The absence of an internal combustion engine coupled with ever increasing customer expectations for modern vehicles has required transmission generated noise to be reduced significantly. The primary source of noise within a transmission is the transmission error from the gears themselves. The elastic deformations of the gear teeth lead to very slight variations from the theoretical rotational position of one gear relative to the other. This variation in load and speed is transmitted through the shafts and bearings to the casing where it becomes airborne and audible. Extending conventional transmission error analysis to a fully coupled system model including the transmission casing enables casing surface node accelerations to be predicted and compared to established targets. Minimising the initial transmission error is essential to ensuring transmission NVH targets are met.

Whilst the reduction of scuffing risk and minimisation of transmission error are often dealt with at a micro geometry level, the achievement of targets for both attributes simultaneously in a high speed gear mesh requires the gear macro geometry to be designed with these goals in mind. Designing the contact ratios of the gear mesh such that a constant contact length is maintained is common practice, however the combination of the application of lead crowning to accommodate gear misalignments, the use of tip relief to reduce scuffing risk, and gear tooth stiffness combine to cause a significant variation in contact length if the macro geometry has not been designed to minimize their affects. This is particularly true where the gear load varies, as the micro geometry required to minimise stress at high load often causes poor transmission error at low load.

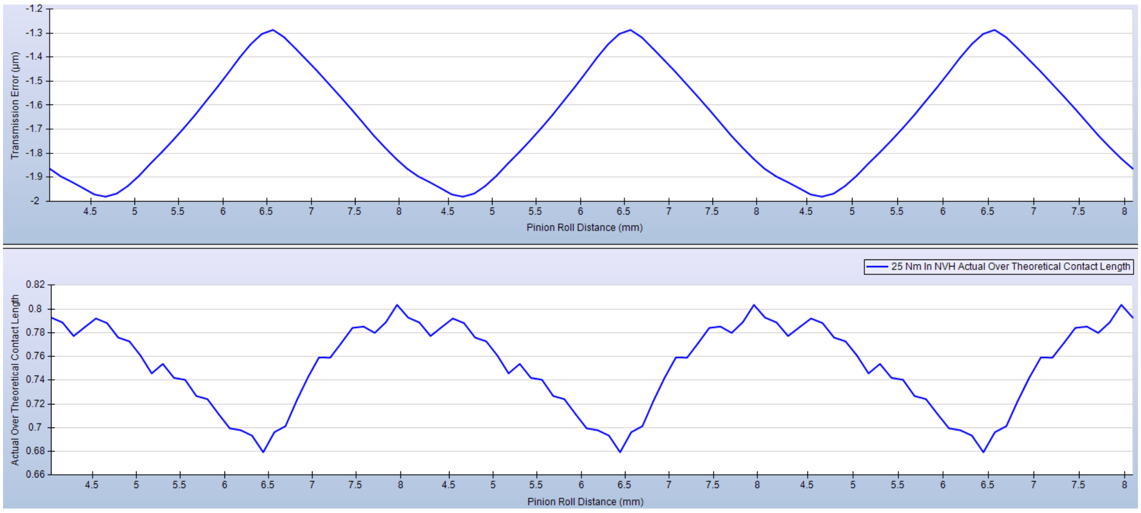

Figure 5 – Transmission Error and Tooth Contact Length Variation

BEARING SELECTION

Selection of standard bearings will be limited by speed capabilities in many instances. The speed requirements may rule out the use of certain bearing types in some cases and may require the use of less standard bearings such as hybrid bearings. Some bearing suppliers have already begun to address these limitations with the design of bearings with a standard construction, by modifying the internal design to reduce friction. This results in an increase in thermal reference speed of roughly 30% and in limiting speed of up to 10%. Cost is only slightly increased due to improved element quality but maintaining a standard construction.

Hybrid bearings combine rings made from bearing steel with rolling elements made from a ceramic material, generally silicon nitride. The advantage of silicon nitride rolling elements is primarily their low density, only 40% of the density of steel. This reduces the inertia forces enabling the bearing to run at higher speeds. A steel / silicon nitride interface also has a low coefficient reducing the heat generated by any sliding contact that may occur in the bearing. The net result is an increase in thermal reference speed of the bearing by approximately 25%, and an increase in limiting speed of over 60%.

The ceramic rolling elements of hybrid bearings also act as an insulator from electrical current. Stray magnetic flux from electric motors in the powertrain can induce electrical currents within the shafts of the transmission. If this is not conducted away through a managed interface it will travel through the rolling element bearings supporting a shaft and can cause damage at the interface between the race and the rolling element in the process. Hybrid bearings have far greater impedance and thus provide good protection from this often over looked potential failure mode.

Hybrid bearings are however more expensive than conventional steel bearings such that they are unlikely to be applied in all but the most extreme of cases. Through detailed analysis and careful system design however it is often possible to operate standard bearings outside of the conventional limits. By analysing the contact stresses within the bearing it is possible to maximize the load capacity of the bearing. Analysis of the speed and load dependent power loss of each bearing also enables the transmission lubrication system to be specified to ensure sufficient cooling in all conditions. Further cooling can be achieved through the design of the bearing mounting. Thermal expansion of the casing can often lead to a reduction in the contact area between the bearing race and the casing, reducing the ability for the bearing to dissipate heat. Mounting the bearing outer race into the casing using a retaining plate ensures that this interface is maintained at all temperatures thus aiding cooling.

SEALING

The conventional automotive transmission input shaft sealing solution is the use of a lip seal, often with an integral dust lip to protect against contaminant ingress. This method works very well in many applications where the prime mover is a combustion engine and the transmission has multiple gear ratios. The input shaft therefore has a maximum input speed of 10,000rpm, or less in most case, and operates at this speed very infrequently and for a short duration. Considering the application of an electric vehicle powered by a high speed motor coupled to a single ratio transmission, this operating environment is drastically changed. The input shaft now rotates at up to 20,000 rpm or more and can be held in this condition far more frequently and for extended periods of time. Today’s electric vehicles are quite capable of travelling over 100 miles at motorway speeds.

Standard lip seals are available in a range of materials in order to account for different environmental conditions and functional requirements. Some of these materials are better at accommodating high speeds than others, but few go beyond peripheral speeds of 30m/s at shaft diameters below 80mm. Reducing the diameter of the seal contact will reduce the peripheral speed, however as the diameter reduces the cross sectional area reduces with the square of the diameter. The heat dissipation capacity therefore reduces rapidly and results in very few lip seals being able to accommodate speeds of 20,000 rpm regardless of diameter or seal material.

If sealing of the high speed input shaft is required then this sealing may have to be segmented into stages to reduce the speed difference between the components. Taking the example of a 3:1 epicyclic gear set using the sun as the input and carrier as the output, the sealing could be achieved by sealing the planet carrier to the input shaft, and sealing the casing to the planet carrier. The 13,300 rpm speed for the first seal then falls within the capabilities of a 25 mm diameter lip seal made from fluorinated rubber.

With concurrent design of the transmission and the motor, sufficient integration may be achievable such that the sealing requirements are reduced or even removed. If external contaminants can be excluded at other (static) interfaces then the primary purpose of the input seal would be to retain the transmission lubricant. This could be achieved with a labyrinth and drain back arrangement. Careful attention must obviously be paid when using such an arrangement that oil cannot pass through the seal when the vehicle, and hence input shaft, is stationary. Complete integration of the transmission and motor such that the motor rotor is essentially enclosed within the transmission and exposed to the lubricant would remove the high speed sealing requirement completely. This can have advantages for the motor in terms of cooling of the rotor, however the transmission lubricant must be dielectric in order to insulate the rotor from the stator.

CASING DESIGN

The casing design for a high speed transmission is likely to follow the same principals as a conventional automotive transmission. Greater emphasis is likely to be placed on the management of lubricant given the points discussed earlier and the likely application in EV / hybrid vehicles. Light metal alloys such as aluminium or magnesium are the obvious material choice due to the low density and good thermal conduction properties, although hybrid metal / composite casings are becoming a realistic production option and are being researched by a number of companies.

Standard practices for high efficiency such as strengthening ribs applied to the casing exterior to minimize internal drag, ensuring high peripheral speed components are not submerged in lubricant, and minimising weight through optimisation of the load path structure should be applied. Passive lubrication distribution systems such as confining lubricant to a “sump” area and metering flow back into the main volume of the transmission to allow cooling and the magnetic removal of debris are advantageous. The segregation of the oil into a separate sump area can also be used to reduce the churning losses within the transmission by keeping the oil level within the transmission to a minimum required by the current operating conditions and hence lessen the drag torque on the gears.

The addition of baffling surfaces to separate the bulk of the oil away from rotating gears can reduce churning losses and increase transmission efficiency by as much as 1%. Baffle surfaces work in a similar way to sump systems but use the initial rotation of the gear to remove the oil from the immediate vicinity. The amount of oil that the gear must turn through subsequently is then controlled and can be greatly reduced. These techniques have been proven to be beneficial but are difficult to analyse and tend to require experience and development to perform at their best.

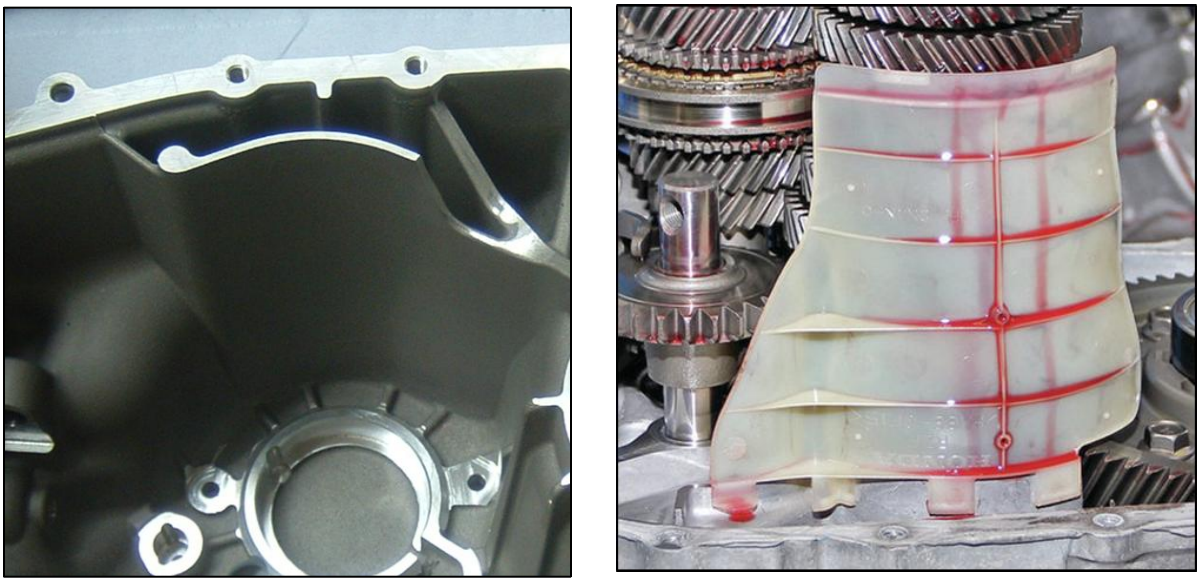

Figure 6 – Design Features for Lubricant Management

The casing structure must also consider the NVH requirements of the powertrain. The noise frequencies generated within the transmission will now cover a much greater range and must not be amplified to a dissatisfactory level. Analysing the housing response to the vibration sources within the transmission, primarily gear transmission error, requires a complete system model but is quite feasible, and ultimately less expensive than developing a solution to an NVH problem on a production driveline.

CONCLUSION

Whilst the design and development of high input speed transmissions for automotive applications poses a new challenge for companies it remains a viable avenue for increasing the power density and efficiency of modern electric and hybridised vehicles. Existing technology has been shown to be capable of being applied to solving the issues proposed when applied correctly and analysed in sufficient detail.

A greater emphasis on system based analysis at a concept level can assist in the selection of the appropriate transmission arrangement, as well as the refinement of the detailed design to ensure that essential targets in areas such as efficiency and NVH are achieved.