Exploitation of Full-Toroidal CVT Technology to a Centrifugal Supercharger for Radical Engine Downsizing Applications

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Abstract

The trend towards downsized engines using pressure charging to maintain performance whilst also delivering improved fuel consumption is just one of the results of the industry wide necessity to reduce CO_2 emissions.

Conventional turbo- and supercharging technologies are more than capable of delivering the required peak power and torque levels from such engines but suffer from a number of compromises. Small turbocharged engines suffer from "lag" under transient conditions and have great difficulty in achieving sufficient low speed torque and responsiveness to provide the launch "feel" of a larger engine. Positive displacement superchargers are, generally, much more able to provide the bottom end response and torque levels but the fixed drive ratio means that they are effectively over-sized and therefore wasteful at higher speeds. Both solutions involve part load losses which compromise some of the fuel consumption savings made by downsizing.

This paper shows how the Rotrex centrifugal supercharger can be combined with a Torotrak full-toroidal traction drive CVT to provide a refined, cost-effective and compact pressure charging solution that overcomes many of these problems. The wide ratio spread provided by such a CVT allows much greater control over the available boost pressure even at low engine speed. Furthermore, a significant part of the speed/load map can be exploited by adjusting supercharger speed in order to control charge air mass flow whilst leaving the throttle wide open - minimising pumping loss. The variable speed Rotrak supercharger permits additional fuel consumption and CO_2 benefits to be derived from downsized engines whilst simultaneously improving driveability and providing a big engine "feel". Additional benefits in comparison with turbocharger solutions include simpler transient AFR control, reduced thermal inertia in the exhaust - allowing faster catalyst light-off and reduced under-bonnet temperatures.

The integration of a wide ratio full-toroidal variator with a Rotrex supercharger plus an appropriate mechanical actuation mechanism and control strategy to form a Rotrak device is described along with the manner in which such a supercharger would be used in a downsized engine application.

Introduction

The legislative reduction in CO_2 emission limits is causing all manufacturers to take radical measures to reduce emissions and an almost universal approach is to downsize engines. Pressure charging to maintain performance is vital and will be essential for customer acceptance of these downsized engines. Whilst simple turbochargers can easily achieve the steady state specific power outputs and peak torque levels required of downsized engines they provide poor low speed driveability, poor dynamic response at low speed and hence significant compromises from a driving enjoyment point of view. The more radical the downsizing, the more pronounced these shortcomings become.

Independent analysts estimate that the market for pressure charged gasoline engines will grow from the current global level of 2.5 million units per year to some 12 million by 2016.

The more established market for diesel pressure charging is predicted to grow from 10.5 million to 16.1 million units in the same period [1].

Turbocharging has been the dominant technology both for diesel and gasoline engine pressure charging for many years. However, the requirements implicit in reducing CO_2 and toxic emissions, downsizing and maintaining good driveability have been forcing more complexity into this technology for some time. Two stage turbo arrangements are increasingly common as are more and more sophisticated mechanical designs for the turbochargers themselves– see Davies et al [2]. However, the issues arising from the need for good low speed response both in small swept capacity engines and in performance derivatives with *relatively* small engines present opportunities for an increased market penetration for superchargers – as we have seen with new installations over the past few years.

There is a great deal of activity in the field of pressure charging and, over the coming years a variety of pressure charging technologies will be applied to downsized engines; some will be more successful than others and ultimately, only the most capable and cost effective solutions will continue in volume production. This paper describes a new candidate in that competition, the Rotrak variable ratio supercharger, a very flexible, effective and simple solution to pressure charging downsized engines, offering excellent engine performance at low cost.

Comparison of a Supercharger with a Turbocharger

Generally speaking, superchargers installed as original equipment have been positive displacement devices, typically of the Roots or Lysholm types. Such a supercharger, being positively driven from the engine crank, can respond to load changes immediately, unlike a turbocharger system that must wait until there is sufficient energy in the exhaust gasses to accelerate the compressor to the required speed. This effect is, of course, the background to the well known "turbo-lag" phenomenon. This means that a supercharger can provide significant boost more quickly than a turbocharger at very low engine speeds. This is of key importance when considering downsized engines. Whilst a small displacement turbocharged engine can easily deliver good steady state performance across the speed range it is more difficult to deliver a rapid torque increase during transient demand from low speed. In fact, the situation is rather worse than a traditional steady state torque curve suggests: during a transient the turbocharged engine never actually achieves the steady state torque of the published curve because the turbocharger speed does not "catch-up" with engine speed until the transient event is virtually complete. A typical

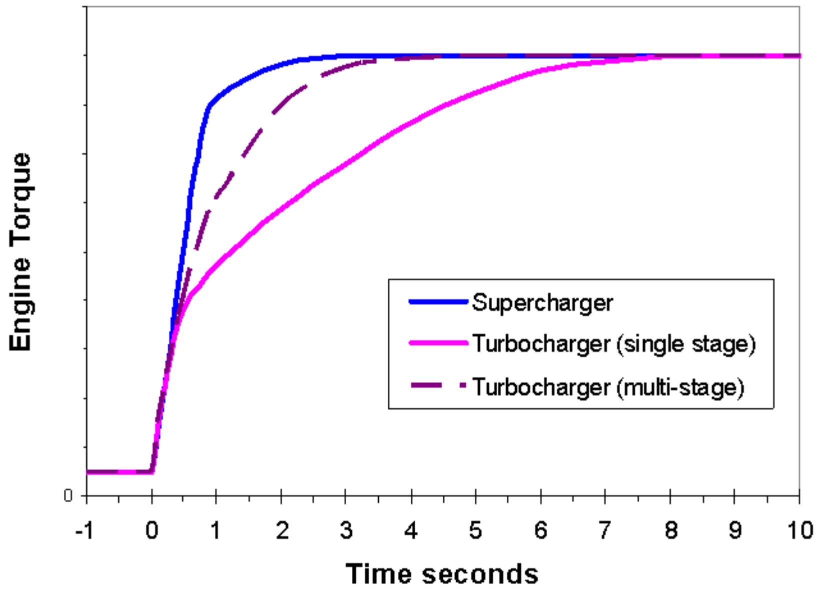


Figure 1: Typical Dynamic Responses at 1500 Engine rpm

response characteristic is shown in Figure 1 for a step increase in load at an engine speed of 1500rpm. The situation becomes even worse at lower engine speeds.

On the larger, more sophisticated, engines found in premium vehicles, this poor response can be partially overcome by using complex dual turbocharger systems. However this approach has a significant cost, weight and packaging penalty together with an equally significant increase in control complexity to achieve smooth driving characteristics.

At higher engine speeds a simple turbocharger provides a more adequate dynamic response. Figure 2 demonstrates this behaviour at 2500rpm where the simple turbocharger performs much better and the twin turbocharger approaches, but does not match, the response of a supercharger.

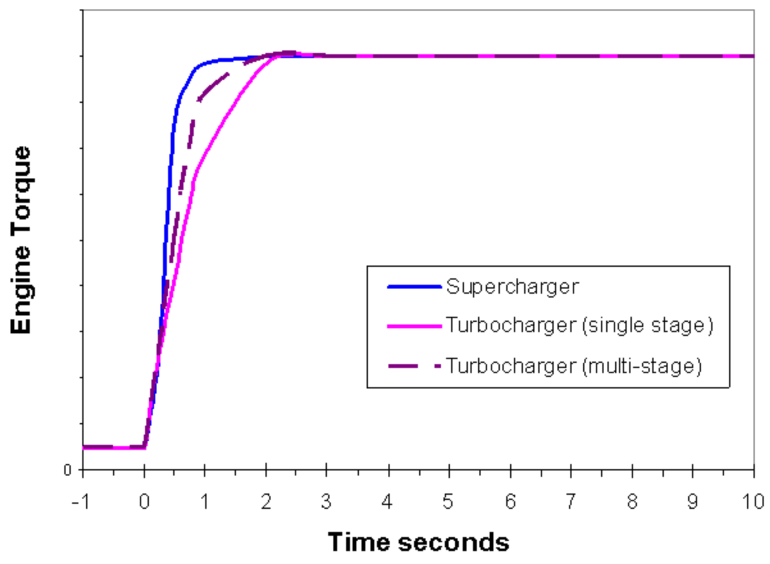


Figure 2: Typical Dynamic Responses at 2500 Engine rpm

To produce a downsized engine that is acceptable to drivers it is crucial to offer a rapid dynamic response at low engine speeds, thus providing the “launch feel” and rapid torque increase after gear shifts of the bigger engine that is being replaced. A supercharger is unbeatable in this respect, providing driving fun and the low speed engine dynamic response so necessary to that enjoyment.

Mechanically driven, centrifugal superchargers have not been popular as original equipment in the past because they need to rotate at very high speed to function and consequently provide very little boost at low engine speed. This is precisely the wrong characteristic for a downsized engine. However, combining a centrifugal compressor with a wide ratio CVT drive system allows a radical recalibration of the characteristic and achievable low speed boost becomes a function of the compressor surge line rather than a drive ratio imposed by the rated speed condition.

A positively driven supercharger provides further advantages: the deletion of a turbine reduces thermal inertia in the exhaust allowing faster catalyst light off and also eliminates thermal stress in the turbine housing – potentially reducing the degree to which full load enrichment at higher engine speeds is required . Another advantage of the absence of an exhaust turbine is the reduced requirement for heat shielding and fewer underbonnet heat soak issues. The fact that the speed of a supercharger is always known also assists in transient AFR control – potentially reducing the incidence of HC “spikes” in particular. Finally, a turbocharger raises exhaust backpressure which imposes a “negative bmep” upon the engine and this contradicts the oft asserted suggestion that turbochargers derive the power required to compress the charge by using “waste” energy. On the contrary, just as superchargers take power from the engine in order to function, so do turbochargers, only the means is different.

The Rotrex Centrifugal Supercharger

Every turbocharger used on an automotive engine incorporates a centrifugal compressor, so they are well understood, well proven, robust, reliable and very cost effective. However, as mentioned previously, a centrifugal compressor has to be driven at high speed to produce meaningful boost pressures.

The majority of such superchargers on the market feature an integrated single gear pair providing a step up ratio of the order of 5:1 plus, of course, an additional belt drive step up from the crank pulley. Rotrex superchargers incorporate their proprietary traction drive epicyclic arrangement to provide a step up ratio of up to 13 in one stage, allowing them to run at higher speeds than is generally possible for these devices. The traction drive transmits torque by shearing a traction fluid entrained between smooth surfaces rolling together under significant Herzian contact stress – there is no metal-to metal contact. As the fluid is entrained between the surfaces high elasto-hydrodynamic pressures, which are necessary for effective traction drive, are generated, the traction fluid undergoes a glass transition in this region and transmits torque very effectively. This is very different from a conventional gear mesh where the drive is transmitted by bending loads on the gear teeth. This arrangement eliminates the geometric constraints on maximum achievable ratio using a geared epicyclic and the higher ratios possible with a traction drive epicyclic are a major advantage. Figure 3 shows a typical Rotrex centrifugal supercharger and Figure 4 shows an exploded view of the traction epicyclic arrangement.

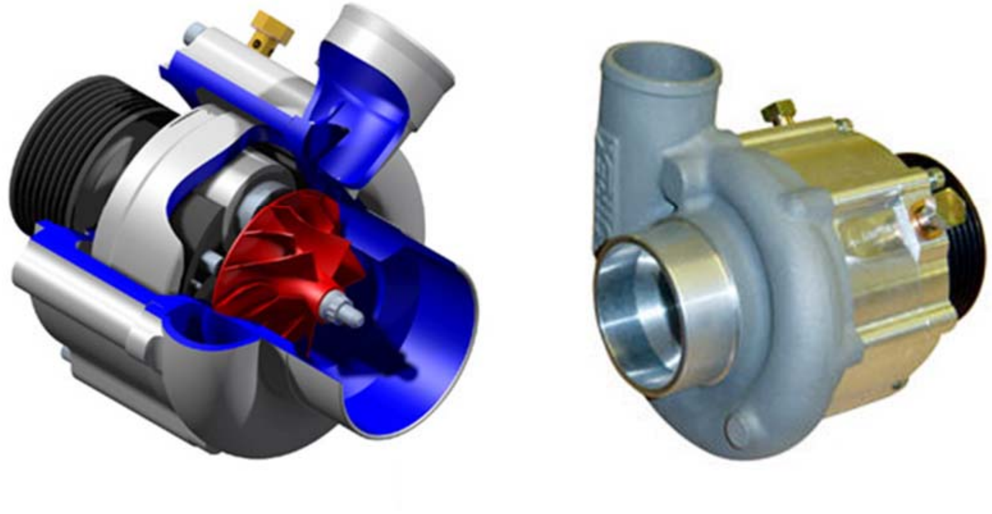


Figure 3: The Rotrex Supercharger with Traction Epicyclic

Figure 4: Rotrex Traction Epicyclic

An intriguing feature of the traction epicyclic design is that the compressor shaft actually forms the sun "gear" of the epicyclic and is trapped between the three cylinders forming the planets. As a consequence of this the compressor shaft requires no bearings and only simple flanges to provide axial location. The overall Rotrex centrifugal supercharger package displays the high adiabatic efficiency of the centrifugal compressor, high mechanical efficiency, low noise and long life in a small, power dense package. Compressor scalability is, of course, similar to turbochargers and quite able to cope with the range of application represented by automotive demands.

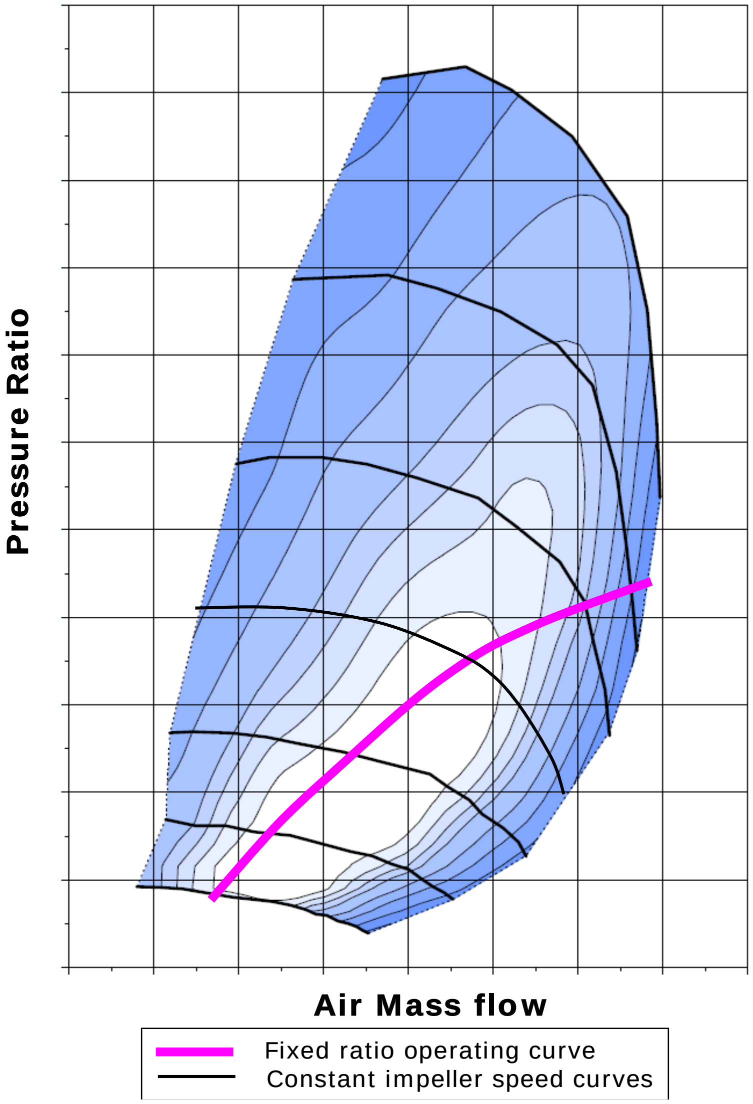


Figure 5: Typical Fixed Ratio Centrifugal Supercharger Operating Map

Typically, these superchargers have been driven at fixed ratio in passenger cars and are used to enhance ultimate vehicle performance. Figure 5 shows the WOT operating line on a typical compressor map – from this it is evident that the characteristic produced is a boost pressure which rises with mass flow – or roughly with engine speed at full load. In fact, little useful boost is produced below 2500 to 3000 RPM so the engine characteristic becomes very sporty and stimulating to drive. However, this is far from a suitable characteristic for a downsized engine as, at launch or in low to mid-speed transients the engine produces no more torque than a naturally aspirated engine of the same swept capacity. Furthermore, such a characteristic would not provide the fuel consumption improvement which is the objective of engine downsizing because the driver would be forced to use high engine speed and low gears to compensate for the lack of torque when engine speed is low.

The Benefits of a Variable Drive Ratio Centrifugal Supercharger

The problem inherent in a fixed ratio drive as far as full load is concerned is the inability to access the area of the map to the left of the operating line shown in Figure 5. The great advantage of a wide ratio variable speed drive is that not only is this area made accessible but virtually the entirety of the map can be exploited. This is shown in Figure 6 and clearly provides huge flexibility to design a full load boost curve to more or less whatever shape is required within the constraints of the surge line on the left of the map and the choke limit on the right. Clearly variable drive offers the potential to increase boost at low engine speeds whilst also controlling maximum boost at higher engine speeds and also, with much greater precision, under part load conditions. By controlling supercharger speed relative to engine speed, the pressure ratio can be matched to the engine requirement under all load/speed conditions requiring a pressure ratio higher than 1. This opens the possibility of controlling engine load by boost pressure, and therefore implicitly by supercharger speed, in the boosted area of the speed-load map. The throttle could then be left wide open in these areas

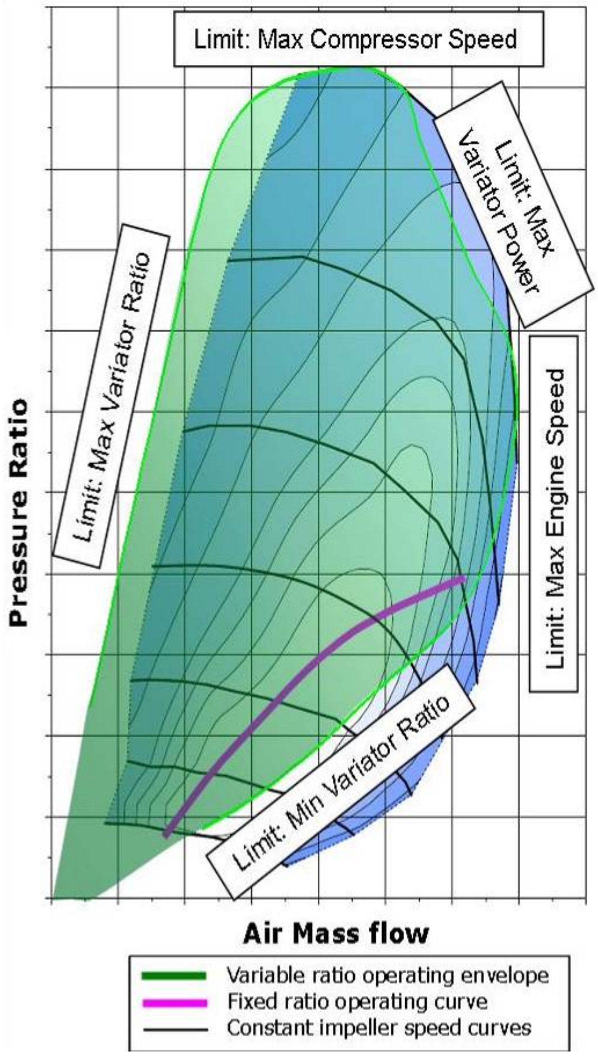


Figure 6: Variable Ratio Operating Envelope

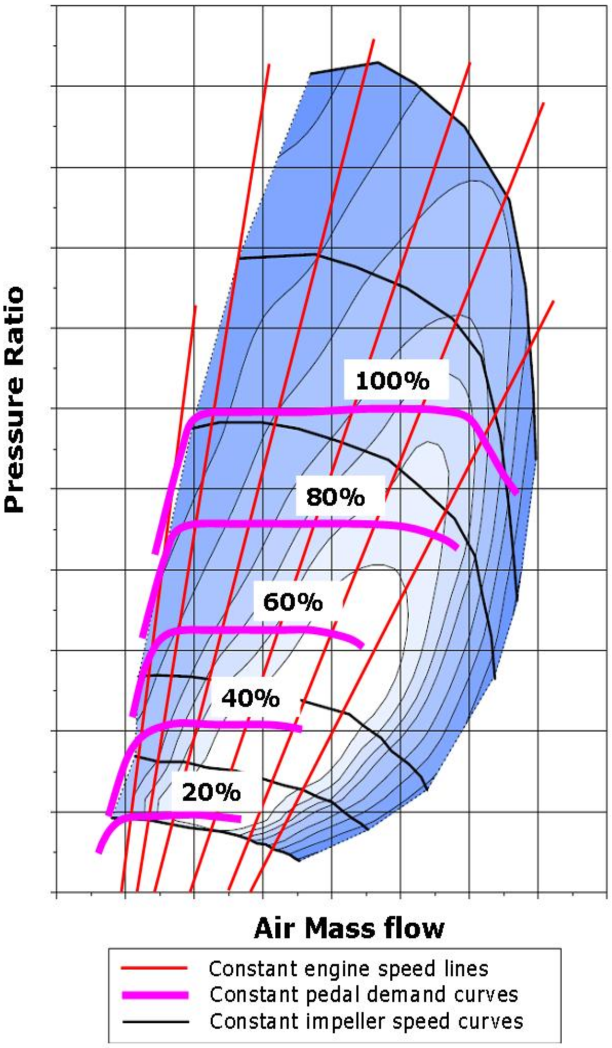


Figure 7: Part Load Operating Conditions

reducing pumping losses and further improving CO_2 emissions. There are some challenges with respect to control of transients under this operating regime but these are not regarded as insuperable.

If we now examine Figure 7, we can see that we can achieve a very different full load, or 100%, boost curve in comparison with the original fixed drive ratio supercharger especially if we consider the lines of constant engine speed which extend generally from the bottom left towards top and right of the graph. This curve will provide dramatically better torque at low speed and a much more useable torque curve in general. Consider now the part load conditions which are shown as curves of reducing proportions of maximum boost. Analysing these operating conditions reveals that the ideal variable drive ratio can be defined as a family of curves covering the various load conditions, see Figure 8. This demonstrates that, for those areas of operation where boost is required to achieve the target bmep, it is feasible to control engine load by means of boost ratio and therefore supercharger speed rather than by means of the throttle. This will significantly reduce pumping losses and further contribute to fuel consumption improvement.

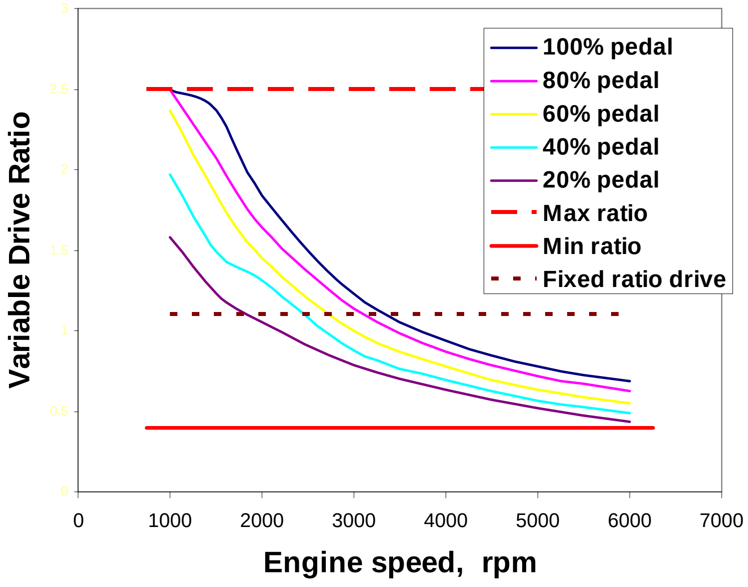


Figure 8: Variable Drive Ratios for Part-Throttle Operating Conditions

It is also appropriate to consider the operating conditions where the required load is sufficiently low that throttling is still required. Under these conditions the supercharger speed must be minimised as there is no need to generate boost and the supercharger drive represents a parasitic loss. Traditionally, many supercharger drives are de-clutched under such circumstances. However, if a variable drive can provide a sufficiently wide ratio it may be possible to eliminate this clutch and drive the supercharger slowly enough to avoid unacceptable losses. The envelope in Figure 6 suggests that this may indeed be possible for the Rotrak machine – especially if extending the ratio spread beyond the 6.25 of today to 7 or more, as is anticipated in the Rotrak application, does prove possible.

The Rotrak Supercharger

The Rotrak supercharger combines the Rotrex technology described above with Torotrak's full-toroidal, wide ratio variator or CVT technology – both of which rely on traction-drives to deliver their respective contributions. The Rotrak combination provides a means to actually deliver the working envelope shown in Figure 6 in a compact, reliable, cost-effective unit.

Compared to fixed ratio superchargers this device massively improves both the boost performance at low engine speed by applying a large overdrive capability – typically in excess of 90:1 overall ratio from crank to compressor wheel whilst also maintaining the appropriate ratio, say 15 to 20:1 at rated engine speed. Furthermore, as discussed above, the part load engine efficiency can be optimised by using the under-drive capability to reduce the ratio to less than 15:1 when no boost is required, thus minimising parasitic losses.

The compatibility of the traction drive technologies permits a highly integrated design packing the traction epicyclic and the toroidal variator into a common housing, sharing traction fluid and a single oil pump. The result is a very compact and power dense package.

An initial design layout of the Rotrak system with the corresponding block diagram is shown in Figure 9. This particular example employs a relatively limited ratio spread and was targeted at the performance market. Note the compact dimensions achieved for a mechanical variable ratio supercharger designed for maximum impeller powers in the region of 20kW to 25kW. This power capacity is also appropriate for significantly downsized gasoline engine applications in mainstream car applications and current work is focussed on a wide ratio spread device of approximately this rating to be installed in a car in 2011. The technology is easily scaled to higher or lower power requirements and can be applied across the full spectrum of passenger car requirements. Rotrex already produce a family of centrifugal superchargers suitable for a wide range of engine sizes, whilst Torotrak have experience over a range of prototype variable drive units suitable for applications ranging from ride-on lawn mowers, small to large passenger cars, on-highway heavy trucks and agricultural tractors.

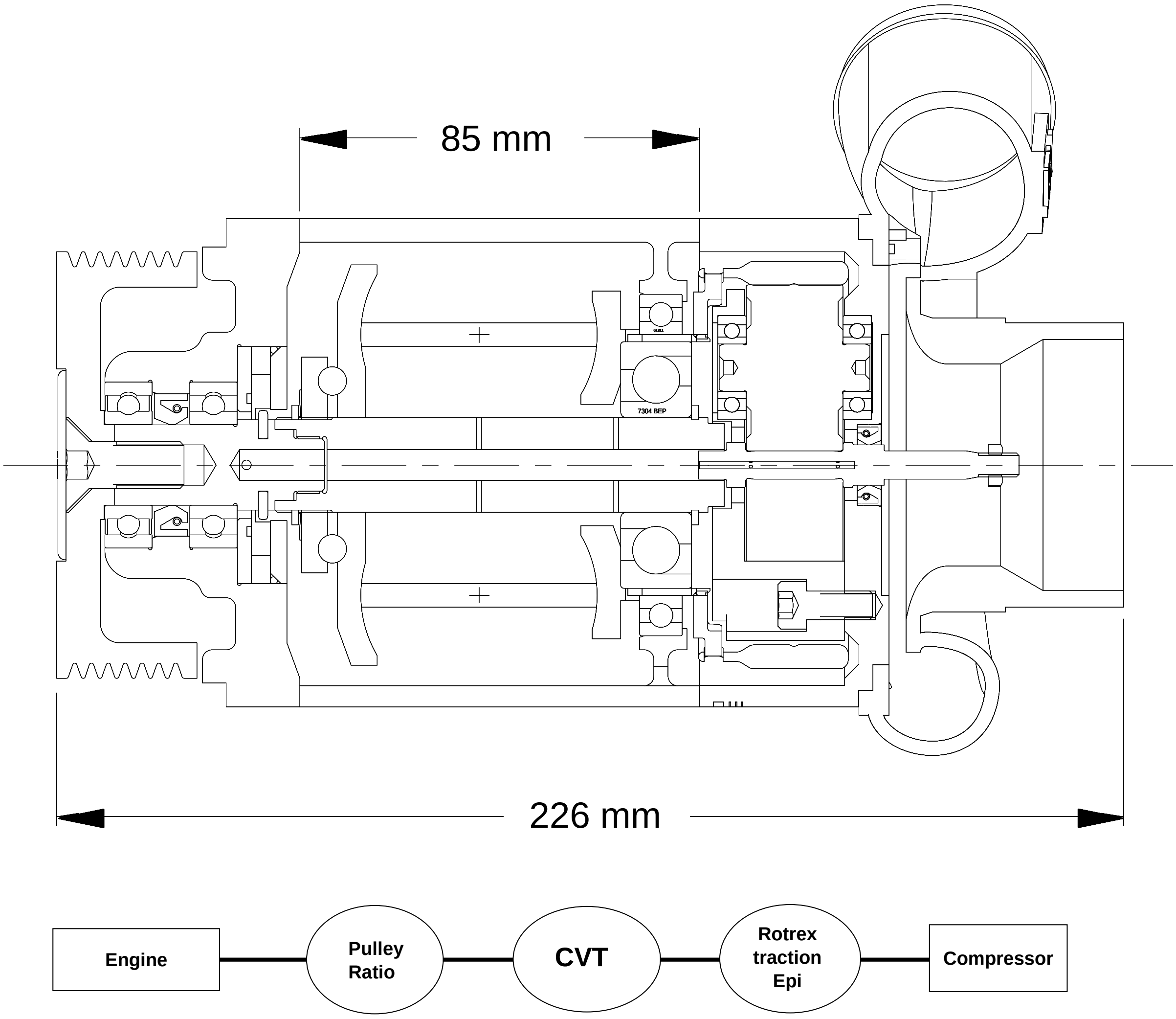


Figure 9: Rotrak Variable Ratio Supercharger and Corresponding Block Diagram

The Full-Toroidal Torotrak Traction Drive Variator

Torotrak is the world’s leading developer of full-toroidal traction drive technology and provides the variable ratio traction drive for the Rotrak system.

This variable drive element is the Torotrak full-toroidal traction drive variator which has a typical ratio spread of 6.25, arranged from an under drive of 0.4:1 to an overdrive of 2.5:1. In this particular application it is likely that a range in excess of 7 will be possible. The Rotrex traction drive and the Torotrak variator operate on precisely the same physical principle which is why both components can share the highly specialised traction fluid used to transmit torque efficiently between two smooth surfaces.

The full-toroidal twin cavity traction drive variator shown in Figure 10 has two toroidal cavities and is designed for use in Kinetic Energy Recovery Systems (KERS) applications requiring considerably higher powers than those of the Rotrak application. The Rotrak variable ratio supercharger drive requires only one toroidal cavity providing a correspondingly reduced parts count and even further improved cost, package and weight.

Figure 10: The Torotrak Full-Toroidal Twin Cavity Variator Configured for KERS Applications

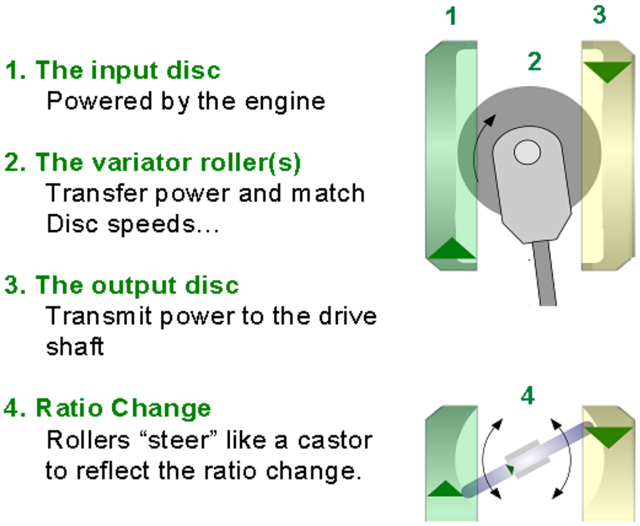


Figure 11: Full-Toroidal Traction Drive Variator Schematic

The operating principle of the variator is explained by reference to Figure 11: the the input disc (1) is driven and power is transmitted via the rollers (2) to the output disc (3). When the rotational velocities of the input and/or output disc change, the rollers automatically alter their inclination in order to adjust to the new operating conditions (4). Power transmission is achieved by traction, i.e. by shearing an extremely thin, elasto-hydrodynamic fluid film (traction fluid [3]) and not through metal-to-metal contact or friction. Hence the name 'traction drive', which is defined in [4] as: "a power transmission device which utilizes hardened, metallic, rolling bodies for transmission of power through an elasto-hydrodynamic fluid film".

The fundamental physics of a full-toroidal traction drive are very similar to that found in rolling contact bearings. Therefore the well known, understood and validated laws defining the relationship between materials, stress and service life applying to bearings are equally applicable to the traction drive variator. These relationships have been further validated by many years and tens of thousands of hours of development and testing undertaken by Torotrak.

The physical size of the variator is determined by the power it is required to transmit. Suitable design of the detail geometry of the contact between the discs and rollers in conjunction with appropriate material selection and an in depth understanding the S-N properties of that material permits the achievement of compact, power dense solutions exhibiting the appropriate life for any application.

Control of the Variator

A centrifugal compressor has a very characteristic power demand which is a function of speed, mass flow and pressure ratio. This characteristic can be used to advantage when considering the control strategy for the Rotrak system and also when defining the loads imposed upon the full-toroidal variator.

Referring to the graph shown in Figure 7, the supercharger drive ratios required at full load are determined by the points where the 100% boost curve intersects with the lines of constant engine speed. Each of these points corresponds with a specific impeller speed and hence the drive ratio for the given engine speed. The same process can be applied to the part boost conditions and these curves are also shown in Figure 7. The compressor power can be easily calculated at each of these points and this is simply converted to torque at the variator output and, through the variator ratio, the variator input torque. This is the torque applied to the engine crankshaft, modified by the belt drive ratio.

Figure 12 shows both the variator input and output torques plotted against engine speed for the Wide Open Throttle condition. The summation of these torques, a parameter known as the Variator Reaction Torque, is also plotted. This Variator Reaction Torque is significant as this is used to control the Rotrak variable ratio drive.

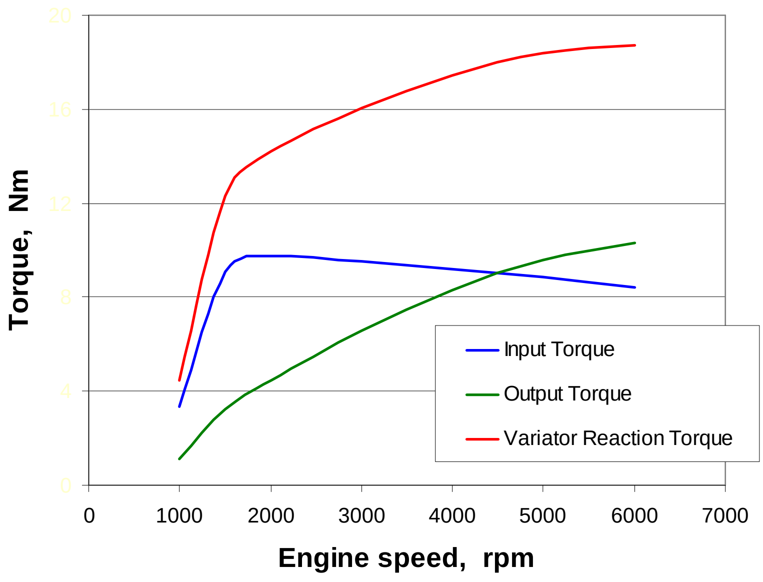


Figure 12: The Variator Torques for Wide Open Throttle Condition

The part load or part boost conditions shown in Figure 7 can also be converted into Variator Reaction Torque curves as shown in Figure 13. The similarity in form of these curves is very interesting because it suggests that the supercharger boost pressure delivered to the engine is a function of the engine speed and the Variator Reaction Torque only. Therefore the control strategy need only define the Variator Reaction Torque – there is no need to control the variable drive ratio directly – or even to know what it is. In fact the ratio of the variable drive is an outcome of this control strategy rather than a controlled parameter under this “torque control” methodology. This permits a very simple control strategy to be employed.

In order to understand Variator Reaction Torque it is necessary to consider the force balance in the CVT disc and roller mechanism as shown in Figure 14. A feature of the full-toroidal traction drive variator is that the summation of the input and output torques of each roller, known as the Roller Reaction Torque, is experienced at the roller axle. For equilibrium the tangential forces acting at each contact point between the roller and the discs are the same, however, the ratio dictates that the roller is inclined at an angle between input and output discs and this will dictate the torques. The input torque is the product of the tangential contact force and the distance from that contact point on the input disc to the variator centre line, R_i in Figure 14, similarly the output torque is the product of the tangential contact force and the distance from that contact point on the output disc to the variator centre line, R_o. Thus the force applied to the roller axle is a direct function of the reaction torque.

This causality can be reversed, such that if a force is applied to the roller axle then it will define the torques generated at the input and output discs in proportion to the ratio. It therefore follows from the earlier discussion that the boost pressure can be controlled simply by modulating the force applied to the roller axle – there is no need to know or control the variable drive ratio.

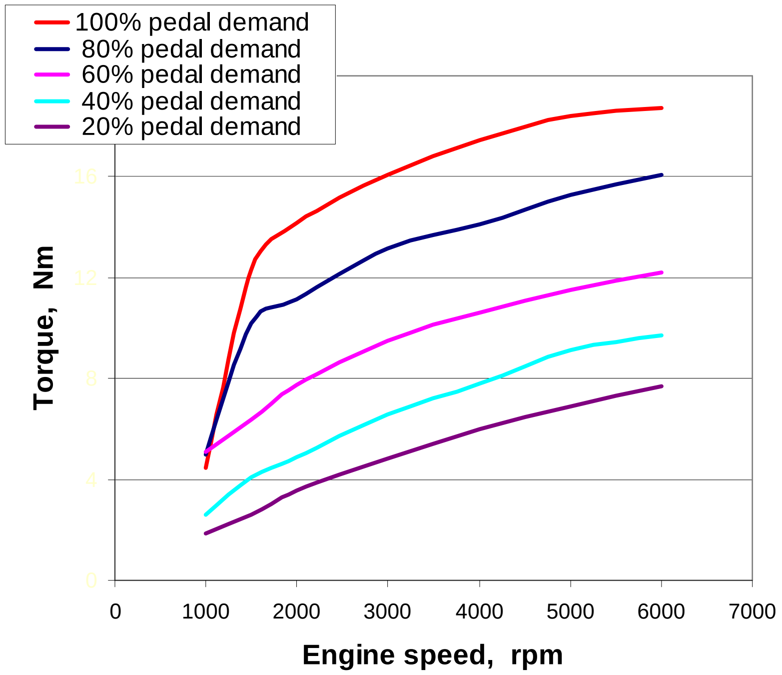
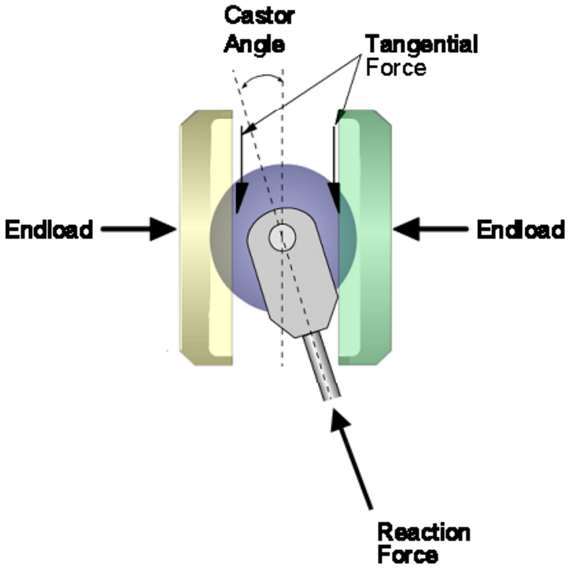


Figure 13: The Variator Reaction Torques for Part Load Conditions

The application of a castor angle to the roller carriages (as described in Figure 14) enables the rollers to ‘steer’ to a new angle of inclination and hence achieve the correct variator ratio that results in perfect load balance of the rollers. This maximises the power density of the variator.

The fundamental principle of torque control previously described is now redefined as a control process. The required boost pressure can be interpreted as a Variator Reaction Torque requirement. This reaction torque requirement in turn defines a force applied to the roller axles.



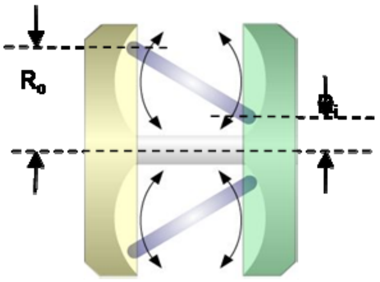


Figure 14: Variator Force Balance

This approach is explained in Figure 15 using a simplified single roller model. Applying a reaction force F to the roller creates reaction torques (Ta and Tb) at the variator discs and consequently an acceleration of the two inertias (engine side inertia A and output side inertia B). This may change the speed of the engine and/or output inertia resulting in a change of variator ratio. Due to the castor angle, this ratio change happens automatically.

If no control force is applied the variator it cannot transmit torque and the ratio will self steer to the minimum value when the force applied to the mechanical stop will allow it to drive the impeller at a minimum speed. This also minimises the referred inertia of the system at the crankshaft thus minimising the belt and variator loads during engine start.

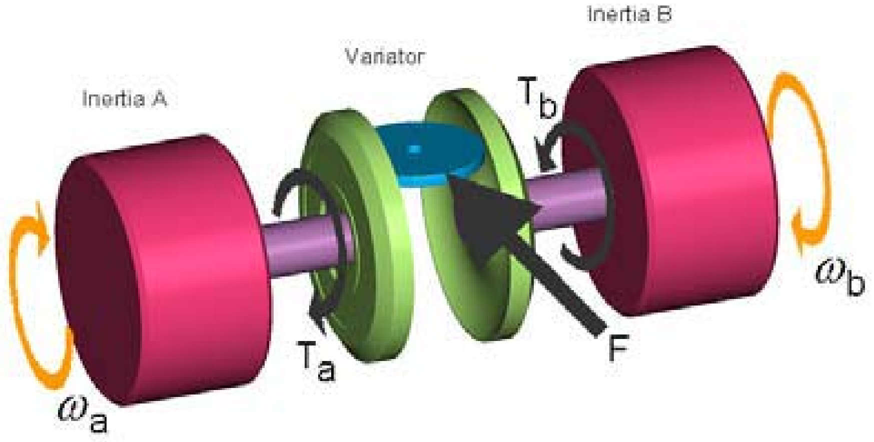


Figure 15: Principle of Torque Control

Defaulting to no control effort also means that the default boost is the minimum which is regarded as the best fail safe condition, protecting the Rotrak system from excessive and damaging loads, the engine from excessive boost and also providing a benign drive-home mode which still offers the full naturally aspirated performance of the engine.

The response to a step change in load is easily accommodated by the torque control philosophy. Consider a steady state cruise condition requiring a low level of boost pressure. A step increase in driver demand requires the impeller speed to increase quickly in order to increase the boost pressure. Hence the impeller, traction epicyclic and variator output side components must all be accelerated. Power is required to accelerate the inertia of these components at the required rate. This inertial power is additive to the steady state impeller power which is a function of boost pressure and impeller speed. Therefore it is clear that the power requirement to achieve a defined acceleration rate changes as a function of the variable drive ratio – this is very difficult to define and track accurately if trying to control the variator ratio. However by setting a Variator Reaction Torque demand, which effectively limits or defines the torque reacted, the split of power delivered to compress the air (the steady state requirement) and that needed to accelerate the component inertias occurs due to the laws of physics with no additional control intervention. Hence the rate of pressure increase (which is approximately the rate of engine torque increase) is defined by the controlled application of a Variator Reaction Torque – this is a huge simplification of the control task and minimises the number of sensors required. It is easy to close the control loop on either impeller speed or boost pressure or load applied to the crank as desired for the particular application. Simply reduce or increase the Variator Reaction Torque in order to increase or decrease the acceleration of the compressor wheel.

Tolerance of Cyclic Vibration

Torsional oscillations are ever present at the micro-level from the cylinder firing events, especially at low engine speed, high load conditions. Whilst the belt drive will attenuate these slightly the variator is further able to absorb most of the transient acceleration seen at its input. This is a beneficial consequence of the decision to define the reaction torque of the variator, which is therefore only able to transmit a specified value of torque to the impeller, or output, inertial load. So as a sudden input torque transient occurs during an otherwise steady state condition, the increased input torque cannot be transmitted to the output inertias since this requires an acceleration of the inertias which in turn requires an increased reaction torque (which is limited or defined by the control input), instead the ratio will tend to downshift, thus maintaining the output inertias at a constant speed, hence constant boost pressure.

In this way the Rotrak system effectively isolates the impeller from cylinder firing transients and does not impose significant loads due to rapid torsional oscillations back onto the engine crankshaft or the belt drive. However, at the macro-level it should be remembered that the varying drive ratio will alter the inertial load experienced by the FEAD and engine as the variator ratio changes.

Summary and Outlook

The Rotrak Variable ratio supercharger dramatically improves the capabilities of the mechanical centrifugal supercharger. Levels of boost at low engine speed otherwise unattainable for such a device are achievable combined with excellent transient response characteristics – very significantly better than can be attained with turbocharger systems. This allows downsized engines to deliver “big-engine” feel including an excellent launch characteristic and low speed performance.

The Rotrak machine combines the well proven traction drive technologies from Rotrex and Torotrak together with the ubiquitous centrifugal compressor found in most turbochargers into a small, light, power dense and very effective pressure charging solution.

Proof of concept prototypes are undergoing rig tests at the time of this conference and a car will be running early in 2011. The design is easily scalable to different ratings, and can be used alone, as described in this paper, or in combination with a turbocharger as the first stage of a two stage system. For compressor powers up to about 25 kW the basic layout would be broadly along the lines shown in Figure 9.

Overall, on the basis of a significant amount of analysis at the concept level, the Rotrak machine has great promise in that the weight and package will be very competitive, functionality is impressive and the cost analysis work to date also suggests that the product should prove attractive in the marketplace. The current emphasis has been on petrol engine applications but there may also be opportunities for diesel engines where the reduction in exhaust thermal inertia may prove of even greater interest as emissions legislation severity increases.

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