

Analysis and verification of torsional vibration attenuation in automotive powertrains using electromagnetic powersplit transmission

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Summary

A two rotor power split device is described. The unique properties of the Magsplit, and the broadband vibration attenuation are discussed, where reference is made to dynamic models and simulation and ultimately a vehicle based dynamometer rig is described. The test rig is used to validate simulation results and to physically demonstrate the ability of the system to provide broadband attenuation of vibration. The potential deletion of the incumbent vibration control devices from the drivetrain, such as dual mass flywheels, is validated.

Keywords: powertrain, demonstration, HEV (hybrid electric vehicle), PHEV (plug in hybrid electric vehicle)

1 Abstract

This paper is focused on the performance of a magnetic Powersplit (MAGSPLIT) system and specifically seeks to show the significant drivetrain NVH reduction capability inherent in this new type of system. The system and NVH characteristics are described and experimental results of the system mounted on an engine in a vehicle are shown. These results validate the potential for substantial system cost savings by deleting incumbent vibration control components in conventional drivetrains.

The MAGSPLIT system is an integral part of a hybrid electric vehicle and performs the function of a powersplit device. These systems are dominant in hybrid vehicle drive trains where they are used ensure that the engine is operating at its maximum efficiency at any point in the drive cycle and that the vehicle performance requirement is met. In this arrangement a conventional planetary gear is used where the engine crankshaft is connected to the planet carrier and the output to the ring gear. The inner sun gear speed is controlled using an external motor/generator and by varying the speed of this third rotor a continuously variable gear ratio between the primary rotors can be achieved.

This 3-rotor powersplit system is used in the Toyota and Ford product range. The MAGSPLIT differs from this 3-rotor system inasmuch as it a 2-rotor, magnetic system with input and output rotors only. The variator function is provided by an electromagnetic interaction between these rotors and the stator of a fully integrated electrical machine and it is convenient to consider the 3rd rotor as a virtual rotor, existing as a

magnetic field only. The electromagnetic interaction and gear ratio modulation is performed by electronic control of stator currents interacting with this virtual rotor.

One inconvenient aspect of the 3-rotor system is that the clutch system is deleted and the engine crank is connected (albeit with a damper system) to the drivetrain and the systems can suffer from poor vibration attenuation at this point, and increased reliance is placed on the damper system and associated components. This drivetrain vibration, and the effect on the driver, is causing negative reviews of vehicles of this type [1]. Typically engine borne vibration and crankshaft speed variation would cause the sun gear in the planetary arrangement to transmit vibration into the control electrical machine. This acceleration reflects an inertial reaction torque into the drivetrain causing acoustic noise. The 2-rotor MAGSPLIT oscillates in an equivalent manner except the vibration of the massless virtual rotor does not reflect any inertial torque into the system, and importantly requires no additional control effort to limit oscillation. The result is a broadband NVH filter system that does not consume additional power, and allows the damper system and associated components to be simplified or even deleted from the drivetrain with the attendant cost saving. This advancement is especially relevant for future generations of powersplit hybrids where reduced cylinder counts, use of compression ignition engines and high rates of heat release are becoming ever more desirable.

This paper describes the rotor interactions and the corresponding vibration control and validates these findings with simulation studies and the corresponding measurement of vibration filtration on a specially designed and commissioned test rig system. The findings are further validated by the demonstration of the vibration filtration capability in engine testing.

2 Introduction

2.1 Powersplit architecture

The planetary gear based hybrid powertrain is the most prevalent configuration, accounting for ~82% of US hybrid vehicle sales [2]. The success of the architecture can be attributed to three main factors

1. The architecture is sufficiently flexible such that it can be used for a variety of classes of hybrid vehicles including PHEV and HEV and can also be broadly used as a range extended hybrid vehicle with minimum engine size and large on board electrical tractive power capability. This flexibility of platform makes it largely immune to the uncertainty around the future dominance of specific hybrid gear trains.
2. The system does not require the pure addition of electrical parts onto a largely conventional powertrain such as the Q7-etron for example [3]. This makes the system much more cost effective since the hybrid platform is delivered without pure addition meaning as the architecture (and power levels) develop the additional on-cost shows minimal growth.
3. Other factors such as good efficiency and the absence of gear shift dynamics also lead to enhanced customer acceptance, although it must be noted that the potentially complex control architecture can be a barrier to adoption by many OEM's, but leading adopters of power split argue that adding complexity to software is justified if the hardware sees benefits in terms of cost and/or complexity.

These reasons provide a compelling argument that the power split architecture will remain the dominant architecture within the widely speculated classes of xHEV's. Several challenges for this architecture remain, specifically, the reduction of drivetrain NVH to a point where low cylinder and/or compression ignition engines can be adopted.

2.2 Conventional 3-rotor systems

Whilst many variants of the powersplit architecture exist the so-called "input split" single mode system is most prevalent. In these systems the engine is connected to the planet carrier of a conventional planetary gear, and the output to the ring gear. The speed ratio between these two rotors is controlled by varying the speed of an electric motor/generator connected to the sun gear (3rd rotor). This motor/generator (termed MG1) delivers positive and negative speed variation to the rotor depending on whether an overdrive or

underdrive speed ratio is required (where in this case underdrive and overdrive are defined w.r.t to the intrinsic speed ratio, not a speed ratio of unity). This speed, coupled to the reaction torque in the planetary gear leads to the flow of electrical power either into or out of the drivetrain, and hence the system is termed powersplit. For the vehicle islanded power system, this electrical power cannot be wholly and indefinitely absorbed by the energy storage system and a secondary motor/generator (MG2) is installed on the drivetrain sink/source electrical power. The system becomes very flexible since

1. The speed of the engine can be changed to reduce the specific fuel consumption of the engine
2. Simultaneously to the engine speed change the power delivered by the engine can be modulated by using MG2 such that the vehicle requirement is serviced by the combinatorial power of the engine and MG2. This gives another degree of freedom to optimize the set point of the drive train
3. The system can be operated at engine-off in pure electric mode using MG2 only. The choice of vehicle type, i.e. HEV or PHEV is now solely dictated by the level of energy storage in the vehicle. (albeit with a different final drive ratio in some examples)
4. By employing a relatively large MG2, small engine and high levels of energy storage the system can be considered as a range extended vehicle.

2.3 Magsplit

At the heart of the Magsplit power split system is a magnetic gear which is functionally equivalent to the epicyclic gear in a conventional power split. As with conventional power split systems the Magsplit incorporates a motor/generator (often termed MG1), however, unlike conventional systems this MG1 machine in a Magsplit is fully mechanically and magnetically integrated with the power split device to create a single component providing two functions. The merging of components and functions is achieved by essentially deleting the sun gear from the system which is the point of common coupling and directly connecting the components (albeit electromagnetically). This approach to integration has the common effect of reducing part count, cost and complexity etc., but in this case, the removal of the sun gear without affecting functionality has the most pronounced effect on the system dynamic performance.

In order to discuss the effect of the removal of the sun gear from the system it is instructive to analyse the analogy between a mechanical and magnetic gear as shown in Figure 1.

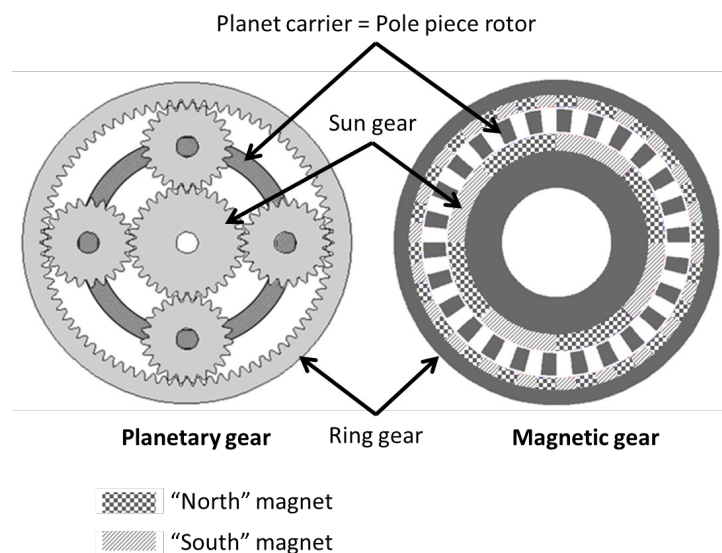


Figure 1. Magnetic/Planetary gear analogy.

The equivalent magnetic system has the inner sun and outer ring gears replaced by the equivalent magnetic system, i.e. an array of North/South magnet poles arranged to rotate on similar structures. However, in the Magsplit system there are two key differences that are exploited

1. The magnetic gear is arranged such that the high speed rotor is placed outermost in the gear (in the place of the ring gear). Whilst this is fundamentally impossible in the case of a mechanical gear which is governed by the requirement to match diameter ratio to teeth ratio, the magnetic gear system is not confined by this principle. It is this high speed rotor (formally the sun in the planetary equivalent) that must be connected to the generator. For completeness the functional ring gear is now placed in the centre of the gear in the space “traditionally” occupied by the sun gear.
2. The high speed rotor, i.e. a rotating array of magnets, is created by electronically switching currents in the windings of a conventional stator to create the equivalent rotating magnetic field. This magnetic field now represents the equivalent field of the magnet rotor, without the mechanical presence of rotating shafts or magnets, and hence the rotating magnetic field is termed the “virtual rotor”. This rotor performs the function of the high speed rotor of the magnetic planetary gear, but also performs the function of the rotor of the generator (MG1) rotor. Hence the two functional rotors in a conventional power split have been combined into one single varying magnetic field represented as a massless, virtual rotor.

This outermost virtual rotor is used to control the reaction torque within the magnetic epicyclic and consequently transmitting engine torque to the drive train. This use of a massless rotor to provide reaction torque leads to unique dynamic behaviour of the system which will be markedly different and it will be demonstrated that the virtual rotor leads to vibration isolation properties that are not achievable with the analogous mechanical system

Consider the powersplit system where the engine crankshaft is connected to the planet carrier/pole piece rotor of a powersplit system and the drivetrain output is achieved at the ring gear (situated in the innermost position in a MAGSPLIT). In this case the sun gear (high speed rotor in a MAGSPLIT) is connected to the variator system which is controlled using a motor/generator (MG1). Having established a quiescent gear ratio for this system it is possible to represent the system using a nomogram as shown in Figure 2.

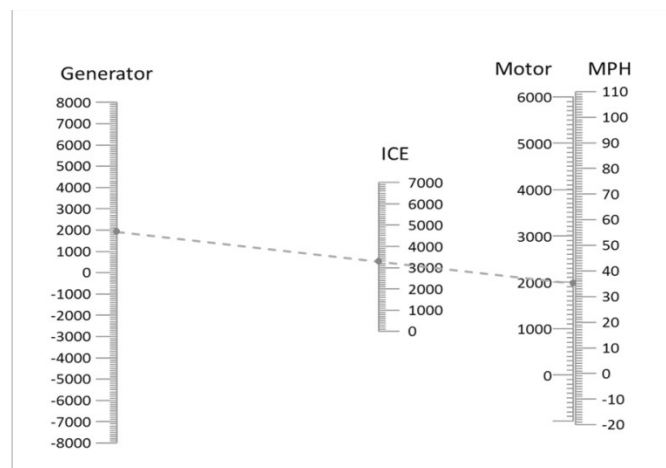


Figure 2. Power-split nomogram (not to scale)

For the system shown in Figure 2 the engine input shaft speed is oscillating due to piston firing events. For mechanical power split systems this speed oscillation is passed to either the vehicle or the MG1 in varying proportions as governed by the dynamic behaviour of the system. The dynamic system analysis is presented in [4] and is not included in this paper.

As the input from the Internal Combustion Engine is oscillating the goal is to isolate this oscillation from the drivetrain (indicated in this case by the Motor section of the nomogram), and in this case this implies that the generator speed (MG1) must oscillate, with the nomogram lever essentially pinned at the Motor

node. Allowing the MG1 rotor to oscillate gives rise to a slightly counterintuitive result where the motor controller must be tuned to essentially ignore the oscillation, but react to an essentially DC torque demand. The stiffness and a damping of the dynamic system are derived from the MG1 controller which is tasked with monitoring the speed of the control rotor and comparing this to a demand speed. The resultant error signal is passed to a controller which will typically create a response based on inputs in proportion to magnitude, and the time integral of error.

For a very “stiff” controller tasked with minimizing the error signal with an oscillating input will lead to high torques and high transient electrical loading of both the motor and the power electronic controller will lead to very high transient powers in the system. The goal then in this case, is to instruct the controller to limit the stiffness and damping associated with its response to the oscillating speed error, and one convenient method in this case is to place the controller in torque control.

Allowing the rotor to oscillate however (in a conventional 3-rotor system) gives rise to an inertial reaction torque which will cause vibration in the drivetrain. In this case for conventional power splits it is tempting to derive a controller to provide active cancellation of the inertial torques. Whilst theoretically possible this type of controller is not prevalent in existing systems since it also leads to very high converter losses and requires a high level of controller intelligence allowing the prediction of incoming vibration events.

The alternative approach described in this paper is to delete all reaction torques at source, and typically the inertial acceleration force can be cancelled by either:

1. Minimising/cancelling the acceleration terms associated with the MG1 by employing one or more vibration cancellation component, such as dual mass flywheels (DMF) and/or pendulum dampers for example.
2. Minimising the mass of the MG1 rotor, and in the case presented here reduce the mass to zero by representing the rotor using a magnetic field only generated by the interaction of the two primary rotors. This magnetic field has zero mass and hence the inertia force is itself reduced to zero.

Whilst the use of vibration control devices such as dual mass flywheels etc. is widely used in automotive drivetrains, it is argued [5] that many of these devices are reaching their performance limits (although alternative structures are presented). Furthermore, it was concluded in [6] that even with a DMF system fitted that “in hybrid driving mode that the noise of the engine is the main noise, and the engagement between the ring gear and reduction gear is always an important source of noise irrespective of whether the engine is turned on or off”. The focus of research presented in this paper is the vibration isolation that can be achieved by reducing to zero the inertia of the MG1 rotor.

It is therefore a relatively simple task of instructing the controller to not respond to, or attempt to cancel, vibration input whilst providing reaction torque to the required steady state level. This slightly counterintuitive result reduces the total oscillating reaction force to zero and maintains the reaction to the steady state force. The result is that the oscillating force input to the vehicle side of the transmission element is itself reduced to zero and steady state transmission is maintained, an approach which does not increase electrical losses, as is the case with active cancellation.

It must be noted that at first appearance reducing the reaction force from MG1 to zero will not allow the vehicle to function correctly since MG1 is expected to provide a reaction torque to ensure that the engine torque is transmitted to the vehicle. In this case it is instructive to consider the relative time frames for a vehicle speed change which may occur over a large number of seconds, i.e. sub-integer Hz and the oscillation input, which for example in a 4-cylinder 4-stroke engine at 3000rpm is 100Hz. [6], [7] and [8] describe controller architectures with cut-off frequencies and drive train resonances at 1.6 and 6Hz and <20Hz respectively being sufficient to provide the required dynamic vehicle response. Hence, without proof by detailed analysis of motor controller design, which is beyond the scope of this paper, it is possible to derive a controller with minimal response at engine firing frequency giving acceptable vehicle performance.

3 Vibration Isolation - Simulation

Having established the characteristics of the MAGSPLIT it is possible to construct a dynamic model of the system, in this case using the Matlab/Simulink platform. The sub-model, shown in Figure 3 is a Simulink representation of the interactions of the rotors in the dynamic system described above. The rotor sub-model correctly represents the component inertias, gear ratio and dynamic interaction and was used to verify MG1 controller output and system response to a simulated engine torsional vibration input.

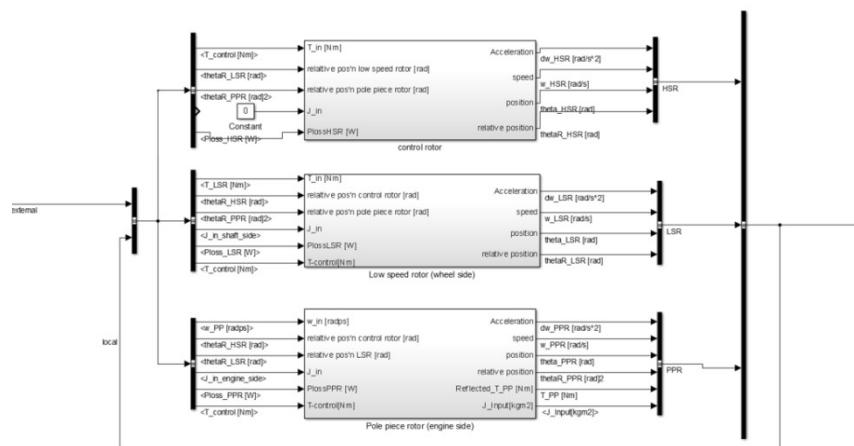


Figure 3. Rotor interaction sub-model in Simulink modelling environment

Figure 4 and Figure 5 show example synthesised engine torque waveforms which can be derived by analysis of the instantaneous pressure waveforms and engine geometry using well documented techniques in, for example, [9] and [10] for the specific case of cranking. In order to illustrate the challenges associated with operating conventional powersplit hybrids with low cylinder-count engines a comparison is made between a 2-cylinder engine (Figure 4) where the peak torque is $\sim 750\%$ of the average and a 4-cylinder engine (Figure 5) where the peak is $\sim 400\%$ of the average. It must be noted in both cases that the input is not purely sinusoidal and contains several higher order harmonics.

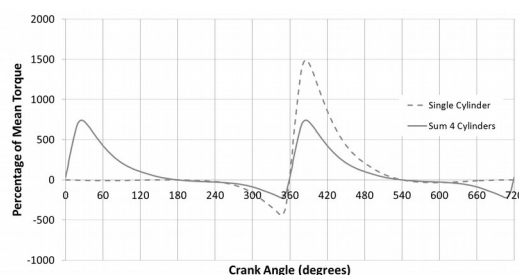


Figure 4. Synthesised 2-cylinder engine torque waveform

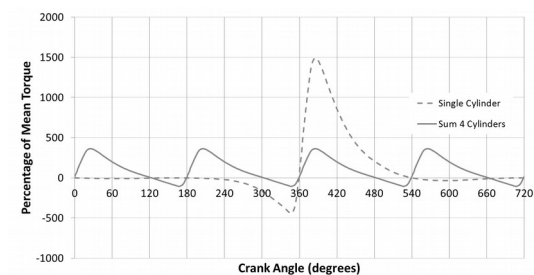


Figure 5. Synthesised 4-cylinder engine torque waveform

During this simulation it is possible to include higher order controller errors linked to signal propagation delays, sample rates and quantisation for example, to assess the influence of these types of errors. This non-

ideal performance of the controller was represented as a series of quantisation events and zero order holds in the simulation using published drive parameters, a detailed description of which is beyond the scope of this paper.

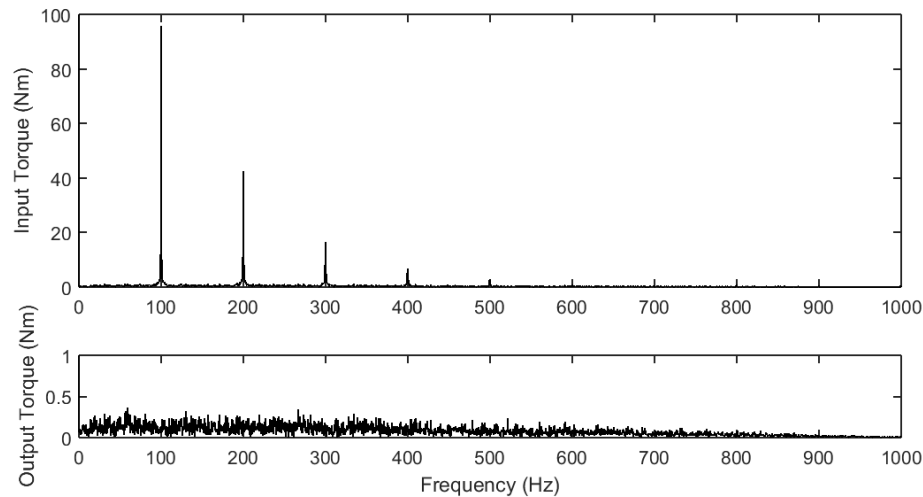


Figure 6. Input and output torque waveforms from Simulink simulation.

Whilst a detailed review of the modelling techniques adopted is beyond the scope of this paper it is instructive to identify an expected frequency response from a Magsplit system. Figure 6 shows the FFT of a typical input torque waveform and the associated output torque FFT calculated using the Simulink model shown in Figure 3. The average engine input torque in this case is approximately 100Nm. It can be observed in Figure 6 that the output rotor is not responding to these very distinct frequency inputs and the system described with zero MG1 rotor inertia does indeed give rise to minimal vibrations in the output. The low level of vibration shown across all output frequencies is in this case caused by the non-ideal controller operation discussed.

4 Experimental Validation

The Magsplit transmission was integrated into the target vehicle, which is a high volume production vehicle that is currently marketed with a standard, non-hybridised drivetrain. Whilst it is commonplace for OEM's to hybridise standard platforms it gives rise to a number of technical challenges, i.e.

1. The engine is not optimised for hybrid operation, as in this case where a 2-cylinder engine is used.
2. The vehicle controllers are not well suited to the inclusion of a hybrid controller
3. The packaging space is dictated by that of the original vehicle and the new drivetrain must be packaged without moving any of the main vehicle features or modifying the body-in-white.

The hybridization of the concept vehicle was undertaken with no modifications to the body-in-white and the hybrid transmission (when instrumentation is removed) is volumetrically smaller than the incumbent transmission.

The installation was undertaken in two phases, the initial installation was used to provide a fully instrumented dynamometer system on a stationary vehicle, this included a secondary dynamometer machine to replicate road-load and load the engine, the secondary installation saw the removal of the instrumentation and the vehicle driveable. It is the initial, instrumented installation that is used to generate the results presented in this paper.

The initial installation also required the use of two high bandwidth torque transducers. The first torque transducer was placed on the input shaft to the Magsplit, i.e. placed between the engine and transmission to allow direct measurement of the torsional vibration at the input. The second torque transducer was placed

immediately after MG2 in the drivetrain. This was facilitated by using a series of shaft extensions and spacing elements to the bell housing. For the concept vehicle the hybrid controller was used to interrupt the standard communications platform allowing a high degree of flexibility and calibration control of the vehicle. The integration with the engine was significantly enhanced by the unique vibration filtering capability inasmuch as the broadband nature of the engine attenuation makes the system suitable for low cylinder counts and high rates of heat release without concern for the “downstream” components, furthermore all drive line vibration isolation components were removed and the engine crankshaft was directly coupled to the Magsplit input shaft.

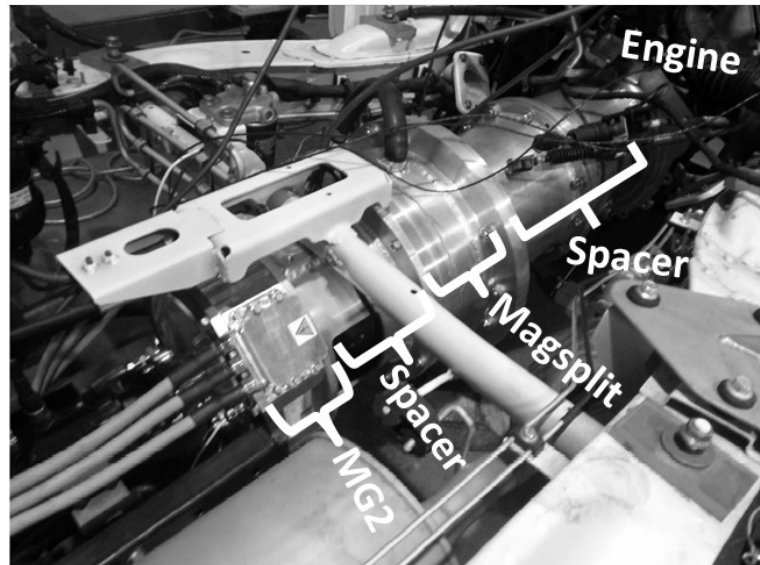


Figure 7. Vehicle installation with instrumentation spacing parts for instrumentation

5 Measured Results

For the purpose of providing repeatable test results with the drivetrain mounted in a dynamometer vehicle the system was configured such that the controller was interrupted to allow the engine to be operated in speed control and the Magsplit and accompanying MG2 was operated in torque control. The dynamometer was operated in torque control to allow repeatable loading on the drive system.

The engine input torque and Magsplit output was recorded simultaneously using a National Instruments LabVIEW based data acquisition system, with a sample rate of 10kHz. A further lower speed LabVIEW based control architecture was used to concurrently record component temperatures and averaged torques and electrical powers etc. These measurements are reported on a 0.5second interval and are derived from averaged signals either captured at 10kHz from analogue equipment or by polling two Newton's 4th PPA1530 power analysers connected to the Magsplit and MG2 for internally averaged data over Ethernet. All data acquisition was synchronised with the commands issued and received over the CAN network, again using a separate slave thread of the LabVIEW based programme, to ensure synchronism.

Figure 8 shows the torque waveforms measured at input to and output from the Magsplit, where it is immediately apparent that the Magsplit is providing near perfect attenuation of the input torque harmonic input. This result is particularly significant given the NVH characteristic of the 2-cylinder compression ignition engine, coupled with the fact that the dual mass flywheel has been removed. Figure 8 (over 0.1 seconds) shows 3 discrete firing events, characterised by the high torque pulses as is predicted by the simplified analysis used to create the waveform shown in Figure 4, however, there is further, lower amplitude, ringing event following the combustion event.

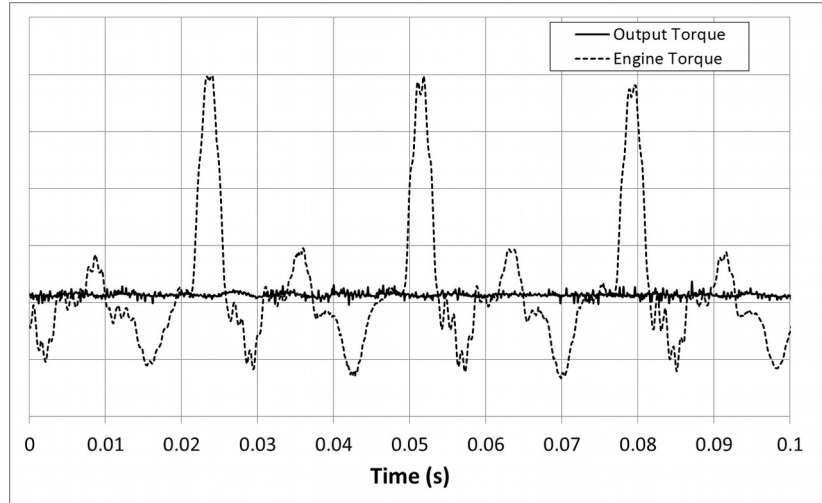


Figure 8. Input and output torque waveforms of Magsplit for engine running at 2150rpm

Figure 9 shows the FFT of both input and output torque waveforms shown in Figure 8, where again the immunity of the output torque waveform to the input harmonic content is again apparent. The inclusion of the zeroth harmonic shows that the Magsplit system is producing a constant torque offset at the value that is required. One feature of the FFT does show a slight response of the system in the 70-75Hz range, and this coincides with the unexpected ringing shown in Figure 8. In order to investigate this ringing it is instructive to analyse a similar data set at a differing speed and Figure 10 shows the similar torque waveforms at 1700rpm and Figure 11 shows the corresponding FFT.

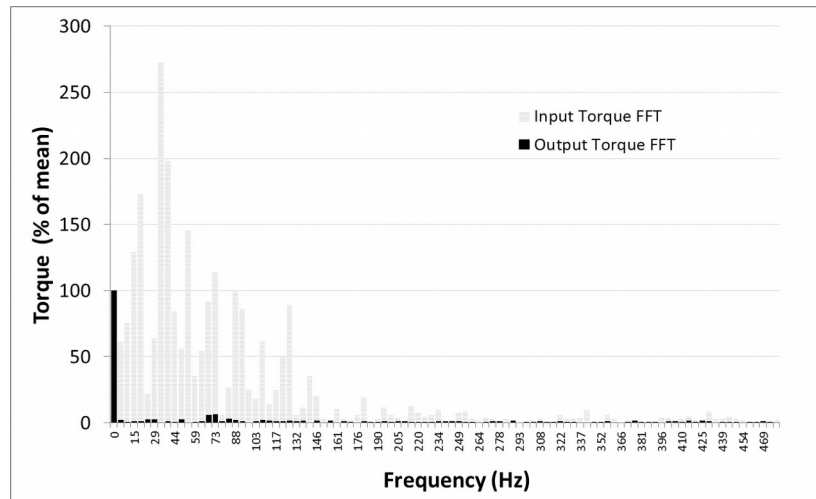


Figure 9. FFT of input and output torque of Magsplit for engine operating at 2150rpm.

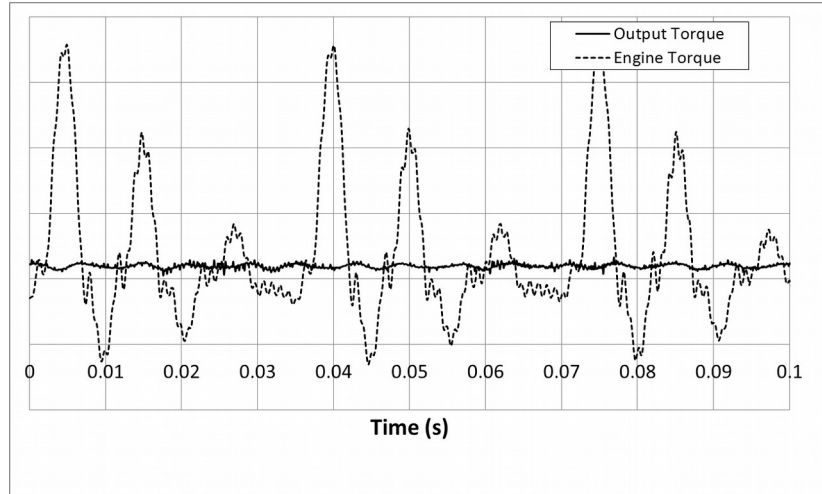


Figure 10. Input and output torque waveforms of Magsplit for engine running at 1700rpm.

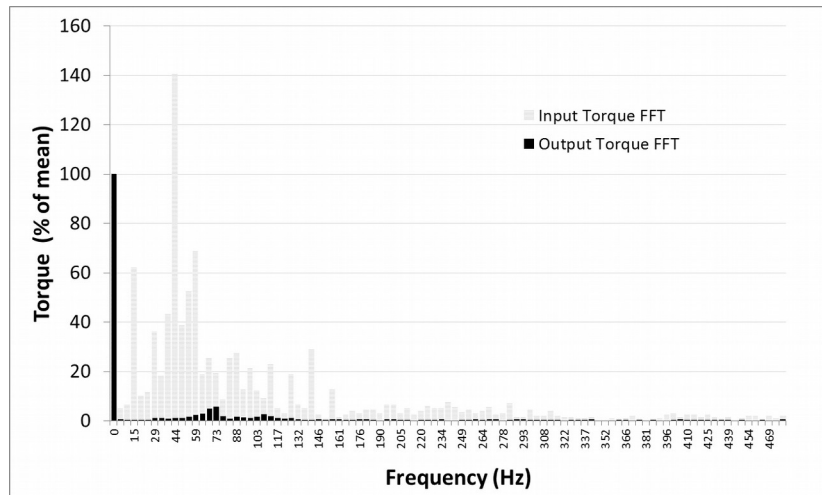


Figure 11. FFT of input and output torque of Magsplit for engine operating at 1700rpm

When inspecting the torque data captured at 1700rpm (Figure 10 and Figure 11) it is apparent that despite the changing harmonic content of the input the attenuation is excellent across the spectrum, although it must be noted that the output is showing a similar response at 70-75Hz. The consistency of the ringing frequency is visually evident when inspecting the waveforms of Figure 8 and Figure 10, where at lower speed (Figure 10) the ringing allows 2 further oscillations between firing events, and at higher speed (Figure 8) the reduced time period only allows one further oscillation between figure events. The presence of the third ringing event in the drivetrain eliminates cylinder compression (or any other synchronous effect) as the cause of the ringing, and leads to the conclusion that this frequency is connected to the resonance of the experimental drive train which necessarily has several shaft extensions and spacing elements. Furthermore the drivetrain cannot be rigidly mounted to the chassis for example since this would over-constrain the system against the necessary movement of the engine on its mounts.

6 Conclusions

The Magsplit system was described and the key functionality of the 2-rotor integrated powersplit discussed. The vibration attenuation properties were described and referenced to existing dynamic models of the system and the interaction with the drivetrain. The system was built and operated on a drivetrain of a demonstrator vehicle with a high level of instrumentation.

The Magsplit system was shown to give an outstanding level of broadband drivetrain vibration attenuation and was shown to be well suited to the application of engines with low cylinder counts and high torsional vibration. The near-perfect attenuation was confirmed in both the experimental and simulation environments. The system was operated without any ancillary vibration control equipment and the ability to delete this equipment from a drivetrain of this type, without detriment to the drivetrain NVH was demonstrated.

A low amplitude fixed frequency vibration was noted at the output of the Magsplit at 70-75Hz, and it was demonstrated that this was caused by vibration of the extended shaft system giving erroneous readings on the torque transducers.

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Stuart Calverley studied at Loughborough University where he obtained a 1st class degree in Mechanical Engineering. He received a PhD in Electrical Engineering from the University of Sheffield in 2001 for his thesis entitled “Design of a high speed switched reluctance machine for automotive turbogenerator applications”. He has worked on a wide range of projects and he designed and built the first prototype magnetic gear system prior to the formation of Magnomatics Limited. He was awarded an EPSRC/Royal Academy of Engineering Fellow which was centered around multi-physics modelling of highly embedded electrical machines for use in gas turbine applications. Stuart has led the development of the Magsplit device at Magnomatics.



Jeff Birchall graduated from the University of Cambridge with a Master’s degree in Mechanical Engineering. He has since been working at Magnomatics where he is currently a Senior Engineer. Over the course of six years Jeff has led a variety of research and development projects, designing and building application specific prototype machines. He has invented several novel design, manufacturing and analysis solutions including the MAGSPLIT2 machine. More recently Jeff has been focussed on automotive based MAGSPLIT applications, working closely with customers to impart knowledge and understanding for complete system design.



David Black graduated in 1994 with a 1st class honours degree in mechanical engineering, and became a Chartered Mechanical Engineer in 1999. He has worked in the Automotive industry for 13 years in series production/new product introduction as well as research and development. David worked for several years as the Director of Advanced Engineering for Dana Corporation and Pierburg GmbH in the area of electro-hydraulic pumps and has led the launch of innovative new products with these companies for major global vehicle manufacturers. David is also a named inventor on several patents concerning automotive motorised pumps for lubrication hydraulic actuation and cooling.