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The PALOS - Project
and
its Significance for Industrial Application

Project data

Project team: Elena Cortona Kanne, Rolf Pfiffner, Patrik Soltic and Felix Weber, Measurement and Control Laboratory (IMRT), Swiss Federal Institute of Technology (ETH)

Project management: Prof. Dr. Lino Guzzella, Dr. Chris Onder and Dr. Alois Amstutz, IMRT ETH

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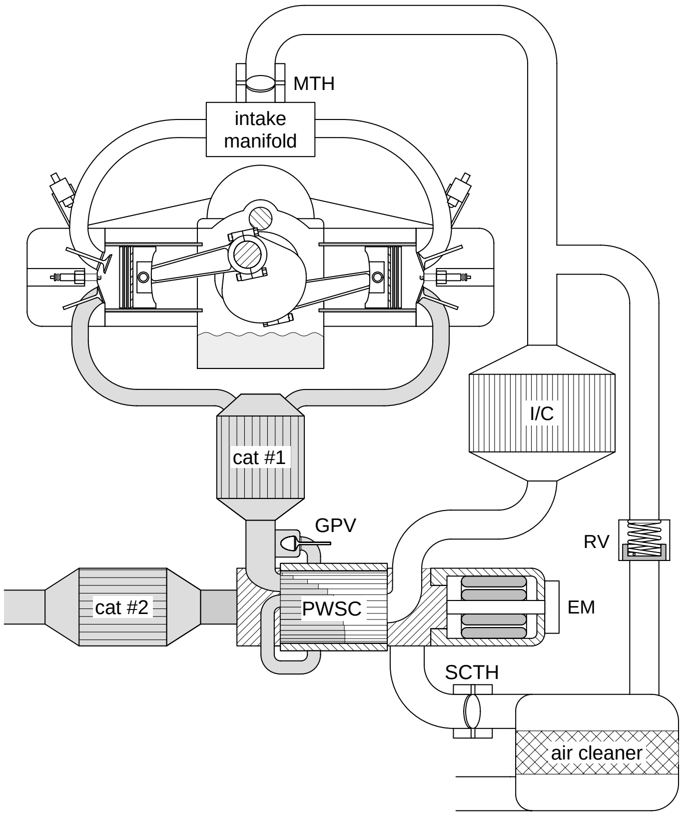

PALOS concept – Downsized supercharged SI engine

Motivation for the project, objectives, boundary conditions

A mid class passenger car needs the average wheel power of 4.5 kW only for driving typical test cycles like the MVEG-95. For the acceleration from 0 to 100 km/h within 10 seconds, however, the same vehicle requires a wheel power of approximately 120 kW. The mean power requirement is more than 26 times less than the power requirement during acceleration. To guarantee the requested acceleration power the engine system has to be designed for this maximum power. As a consequence during steady driving conditions the engine operates under low part load in a range where the energy losses like friction and scavenging work are remarkable compared to the usable energy. Therefore, the engine efficiency is low in part load driving conditions.

Objectives of the PALOS project
The PALOS project (**PA**rt **L**oad **O**ptimised **S**ystem) has the following objectives:
- Contribution to the reduction of fuel consumption of light weight vehicles (<1000 kg)
- Minimal (no) additional costs compared to today's vehicles
- S-ULEV potential for the exhaust gas emissions
- CO_2 emissions in the European driving cycle comparable to electric cars

Method to increase engine systems efficiency
The method chosen in the PALOS project is downsizing and supercharging. Engine downsizing stands for excellent engine efficiency in part load operation, supercharging for high, instantaneous maximum acceleration power.

The four PALOS PhD thesis
The scientific and experimental investigations result in four PhD thesis entitled:
- Part-Load Optimised SI Engine Systems
- Engine Thermomanagement for Fuel Consumption Reduction
- Optimal Operation of CVT-Based Powertrains
- Mean Value Modelling of a Pressure Wave Supercharger (PWS) including Exhaust Gas Recirculation

Significance of the PALOS project for industrial application
The main contribution of PALOS are
- a very thorough investigation of realizable engine concepts toward part load optimisation
- a feasible approach for optimum thermomanagement including novel actuators
- the modelling and experimental verification of the PWS as a suitable supercharger for small engines (< 400 cm^3)
- a step towards optimal real time control of powertrains based on continuously variable transmissions.

The close collaboration with industrial partners during the whole project lead to a high know how transfer from university to industry and vice versa, enhancing the practical significance of university research and teaching.

Acknowledgement
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- Martin Pulfer, BFE
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- Urs Wenger, Swissauto/Wenko AG

Succeeding projects
Together with the Swiss Federal Office of Energy (BFE), the Swissauto/Wenko AG and the Robert Bosch GmbH as Industrial Partner the PALOS project is pursued. The following two topics are investigated:
- The extension of the thermomanagement to the general case of optimal management of the auxiliaries
- Control and application strategies for PWS engine systems

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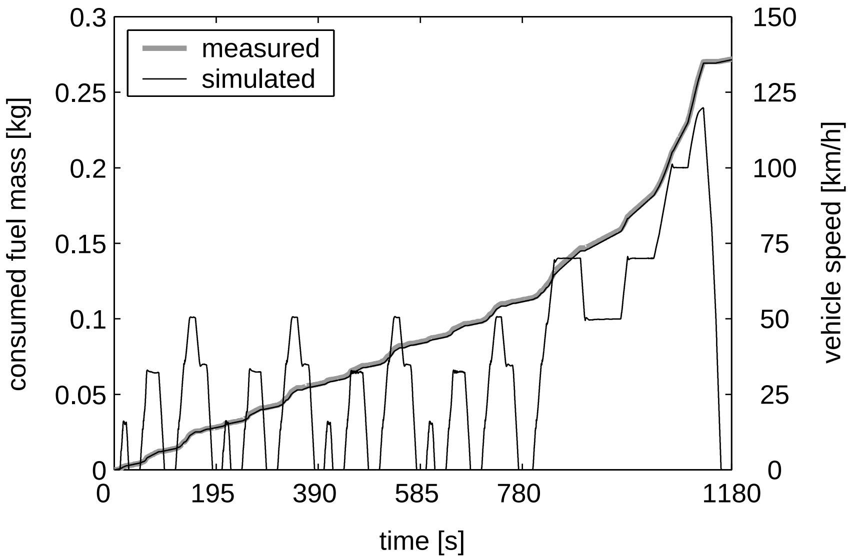
Part-Load Optimized SI Engine Systems

Patrik Soltic



Measured and simulated fuel mass for the new European driving cycle

1.1. Key words

Downsizing, SI engine efficiency, engine concepts, high speed engine, pressure wave supercharged engine, engine simulator

1.2. Abstract

Traditionally, the torque of SI engines has been controlled by throttling the intake air flow. This way the density of the charge and hence the mass which is supplied to the engine is varied. This is a cheap method with an excellent transient behaviour. Unfortunately, a so-called “pumping loop” is induced in the thermodynamic engine cycle. The effect is that the efficiency of the engine decreases substantially for part-load operation. In practice, engines in vehicles are very often operated under part-load conditions so that the resulting fuel consumption becomes high. Many methods have been proposed to control the load without or with reduced throttling: EGR, variable valve timing, intake airflow heating, variation of the engine displacement, reduction of the engine displacement and supercharging. These methods can be applied for each power class of engines.

A special problem arises when engines in the 40 kW class are considered. If such engines are built by applying thermodynamical and mechanical similarity laws, the engines become small in displacement with unusually high maximum speed. In recent production vehicles installed engines are artificially limited in their maximum speed. The consequence is an unnecessarily high displacement and the engines are throttled more than necessary.

To quantify the fuel consumption reduction potential for the class of engines which could be used to power a lightweight vehicle, three SI engine concepts are compared in this work:

– A naturally aspirated engine of classical dimensions which is artificially limited in its maximum speed to 6'500 rpm

– A naturally aspirated engine which takes scaling laws into account. Its maximum speed becomes 11'200 rpm.
– A downsized and supercharged engine with a maximum speed limited to 7'000 rpm.

In addition to the three SI engines, a turbocharged Diesel engine is considered. A Diesel engine has a better part-load behavior and is therefore used as a benchmark.

The fuel efficiency of the SI engines for static operation is simulated using a thermodynamic engine process simulator. The data of the Diesel engine is taken from published information.

The fuel efficiency for all these concepts is simulated for the New European Driving Cycle and for the US Federal Test Procedure. In addition to the simulations, static and dynamic experiments with the downscaled and supercharged engine are performed which demonstrate an excellent quality of the simulation tools.

Powering a vehicle with a curb mass of 800 kg, the Diesel engine achieves the best efficiency. The efficiencies of the SI engines are lower than that of the Diesel engine, but with the downsized concepts, tank-to-wheel CO_2 emissions of lower than 90 g/km in the NEDC are possible.

1.3. Objectives of the thesis

The investigation focuses on the question:
Which stoichiometrically operated SI engine offers best efficiency when used in lightweight passenger cars? Constant improvements in engine electronics, controls, fueling systems and catalyst technology have made the warmed-up SI engine practically free of toxic emissions. The massive application of electronics and control systems led not only to reduced toxic emissions but also to reduced fuel consumption.
The thesis excludes lean burn concepts.

1.4. Main results and new contributions

The main contribution of this thesis is a very thorough comparison of four different engine concepts to achieve best fuel efficiency. The comparison includes a
– conventional naturally aspirated engine
– a downsized high-speed engine
– a downsized pressure wave supercharged engine
– and a Diesel engine

Based on lab experiments and on simulations with an own engine simulator the advantage of a downsized pressure wave supercharged engine is explained. The engine simulation tool and the very detailed comparison of the engine concepts are the main contributions of this thesis.

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Teillast-optimierte Ottomotorsysteme

Patrik Soltic

Zusammenfassung

Das Drehmoment von Ottomotoren wird üblicherweise durch die Drosselung des Frischluftstromes gesteuert. Mit dieser Methode wird die Dichte des Frischgases, und damit die angesaugte Brennstoffmasse, verändert. Das Verfahren ist kostengünstig und hat ein hervorragendes transientes Verhalten. Jedoch wird durch das Drosseln eine sogenannte „Gaswechselschleife" im thermodynamischen Motorprozess verursacht. Die Folge ist, dass der Motorwirkungsgrad im Teillastbetrieb stark abfällt. Im normalen Fahrzeugeinsatz werden Verbrennungsmotoren oft in tiefer Teillast betrieben, woraus hohe Brennstoffverbräuche resultieren. Es wurden viele Methoden vorgeschlagen, um die Lastregelung ohne oder mit reduzierter Drosselung durchzuführen: Abgasrezirkulation, variable Ventilsteuerung, Aufheizung der Frischluft, Variation des Hubraumes, Hubraumverkleinerung und Aufladung. Diese Methoden können auf Motoren aller Leistungsklassen angewendet werden.

Ein spezielles Problem taucht bei der Betrachtung von Motoren der 40 kW Klasse auf. Wenn solche Motoren unter Berücksichtigung thermodynamischer und mechanischer Ähnlichkeitsgesetze gebaut werden, ergeben sich ein sehr kleiner Hubraum und eine sehr hohe Höchstdrehzahl. Heutige Serienmotoren dieser Klasse sind aber künstlich drehzahlbegrenzt. Die Konsequenz ist, dass ihre Hubräume vergleichsweise gross werden, was zu einer unnötig starken Drosselung führt.

Um das Verbrauchsverbesserungspotential für diese Motorklasse zu quantifizieren, werden im Rahmen dieser Arbeit drei Ottomotorkonzepte verglichen:

- Ein Saugmotor klassischer Bauart mit einer künstlich auf 6'500 1/min begrenzten Höchstdrehzahl
- Ein Saugmotor, welcher Ähnlichkeitsgesetzen folgt. Seine Höchstdrehzahl beträgt 11'200 1/min.
- Ein hubraumverkleinerter und hochaufgeladener Motor mit einer auf 7'000 1/min begrenzten Höchstdrehzahl.

Zusätzlich zu den drei Ottomotorkonzepten wird ein Dieselmotor betrachtet. Dieselmotoren haben prinzipbedingt ein besseres Teillastverhalten, deshalb wird der Dieselmotor als Massstab verwendet. Der Brennstoffverbrauch der Ottomotoren im stationären Betrieb wird mit einem Motorthermodynamik-Simulationsprogramm berechnet. Das Verhalten des Dieselmotors wird publizierten Daten entnommen.

Der Brennstoffverbrauch aller Konzepte wird für den Neuen Europäischen Fahrzyklus und für den US-Amerikanischen FTP Zyklus simuliert. Zusätzlich zu den Simulationen werden stationäre sowie dynamische Versuche am hochaufgeladenen Motor erläutert, welche die hervorragende Güte der Simulationswerkzeuge belegen.

Der Dieselmotor verspricht, abgesehen von den deutlich höheren Schadstoffemissionen, den besten Wirkungsgrad beim Einsatz in einem fahrfertig 800 kg schweren Fahrzeug. Der Wirkungsgrad der Ottomotoren ist tiefer als jener des Dieselmotors. Allerdings können mit den hubraumreduzierten Konzepten CO_2-Emissionen tiefer als 90 g/km im NEFZ erwartet werden.

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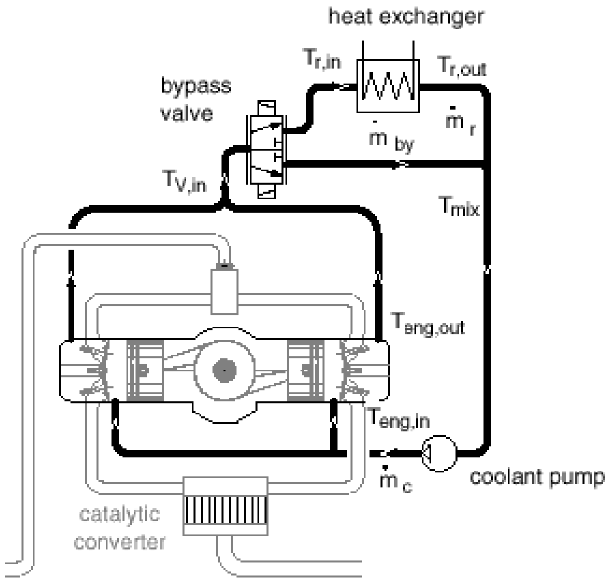
Engine Thermomanagement for Fuel Consumption Reduction

Elena Cortona Kanne



Schematic representation of the cooling system

2.1. Key words

Thermo-management, coolant temperature control, coolant flow control

2.2. Abstract

This thesis analyses the possibility of reducing vehicle fuel consumption by improving engine thermo-management. It proposes a solution for advanced temperature control. In conventional applications, combustion engine cooling systems are designed to provide sufficient heat removal at full load. The cooling pump is belt driven by the combustion engine crankshaft, resulting in a direct coupling of engine and cooling pump speed. It is dimensioned such that it can guarantee adequate performances over the whole engine speed range. This causes an excessive flow of cooling fluid at part load conditions and at engine cold start. As a consequence, the overall fuel consumption increases. Moreover, state-of-the-art cooling systems allow the control of the coolant temperature only by expansion thermostats (usually solid-to-liquid phase wax actuators). The switch type temperature control system does not permit to optimise engine efficiency.

In this work an active control of the coolant flow and of the coolant temperature has been realized using an **electrical cooling pump** and an **electrically driven valve** which controls the flow distribution between the radiator and its bypass. For this purpose the whole cooling system has been modelled. Modelbased feedforward and feedback controls of coolant temperature and flow have been designed, implemented and tested.

The improvements obtained with the proposed configuration in terms of fuel consumption have been measured on a dynamic testbench. Using the modelbased temperature control system

both engine cold start under stationary engine operation and the European Driving Cycle MVEG-A have been tested . The fuel consumption reductions achieved vary between 2.8% and 4.5% depending on the engine operating conditions. Compared to vehicle mass reduction or internal engine improvements engine thermo-management is a simple and flexible solution which should be taken into account for its low realization costs.

2.3. Objectives of the thesis

This thesis focuses on the development of an engine thermo-management to reduce fuel consumption during engine cold start and part-load operating conditions. The analysis and the experimental tests are conducted on a 360 ccm supercharged SI engine.

The following topics are investigated:

- Thermodynamic IC engine model: Both the conventional (belt driven cooling pump and wax expansion element thermostat) and the improved configuration (electrical cooling pump and electrically controlled valve for the radiator bypass) of the cooling system are considered.
- Development of a model-based controller of coolant flow and coolant temperature to reduce fuel consumption
- Verification of the expected fuel consumption reduction on a dynamic test bench.

2.4. Main results and new contributions

- Fuel consumption reduction by coolant flow control
  Controlling both the coolant flow and the coolant temperature the measured fuel consumption reduction due to reduced coolant flow and improved thermal engine conditions varies between 2.8% and 4.5% depending on the engine operation.
- Improved thermal engine behaviour due to model-based temperature control
  The reduction of the coolant mass flow and the simultaneous model-based control of the coolant temperatures permits to reduce the system time constant, avoiding unwanted phenomena such as temperature overshoot during engine cold start
- Fuel consumption benefit through reduced pumping power demand
  In addition, the fuel consumption improves due to the fact that the coolant flow and as a result the demand of pump energy decreases to just a fraction of the original belt driven set-up.
- Electrical auxiliaries powered by recuperated braking energy
  The global energy balance of electrified auxiliary devices and of the cooling pump looks increasingly favourable when the possibility of recuperating vehicle kinetic energy to supply auxiliary devices is considered. The substitution of the mechanical with an electrical pump reflects a general tendency for all the auxiliary devices in automotive applications.

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Motor-Thermomanagement zur Treibstoffverbrauchssenkung

Elena Cortona Kanne

Zusammenfassung
Die Dissertation befasst sich mit der Optimierung des Thermomanagements von Verbrennungsmotoren mit dem Ziel einer Verbrauchsreduktion. In konventionellen Anwendungen wird die Wasserpumpe mittels eines Riemenantriebes direkt vom Motor angetrieben. Das Kühlsystem muss gewährleisten, dass auch unter extremen thermischen Bedingungen (Volllast bei tiefen Drehzahlen und Geschwindigkeiten) genügend Wärme abgeführt werden kann. Durch die direkte Kopplung von Motor- und Pumpendrehzahl über den Riemenantrieb ist die Kühlleistung beim Teillastbetrieb mehrfach überdimensioniert. Dadurch wird der Motorwirkungsgrad verschlechtert, was eine Erhöhung des Brennstoffverbrauchs verursacht. Die konventionelle Regelung der Kühlmitteltemperatur wird mittels eines Thermostats („Wachs Expansions Element“) realisiert. Der temperaturabhängige Öffnungsgrad des Thermostats regelt den Kühlmittelstrom durch den Kühler und damit die vom System abzuführende Wärmemenge. Die durch die statische P-Regelung resultierende Kühlmitteltemperatur ist für normale Betriebsbedingungen (z. B. im MVEG-A Test-Zyklus) nicht optimal.

Thema der Arbeit ist eine aktive Regelung des Kühlmittelstroms durch eine elektrische statt mechanische Wasserpumpe sowie der Kühlmitteltemperatur durch ein regelbares Ventil anstelle des Thermostats. Die modellbasierte Regelung erfordert eine Modellierung des Gesamtsystems mit allen Komponenten. Das regelungstechnisch orientierte Modell wird anhand von Prüfstandsmessungen validiert und für den Entwurf verschiedener Regler verwendet.

Kaltstartmessungen von MVEG-A Zyklen ergeben einen Verbrauchsvorteil von ca. 3%. Das Thermomanagement verkürzt auch die Kaltstartdauer. Im Vergleich zu Massnahmen wie Fahrzeug-Gewichtsreduktion oder innermotorischen Optimierungen stellt das vorgeschlagene System sowohl eine kostengünstige wie auch flexible Massnahme zur Verbrauchssenkung dar.

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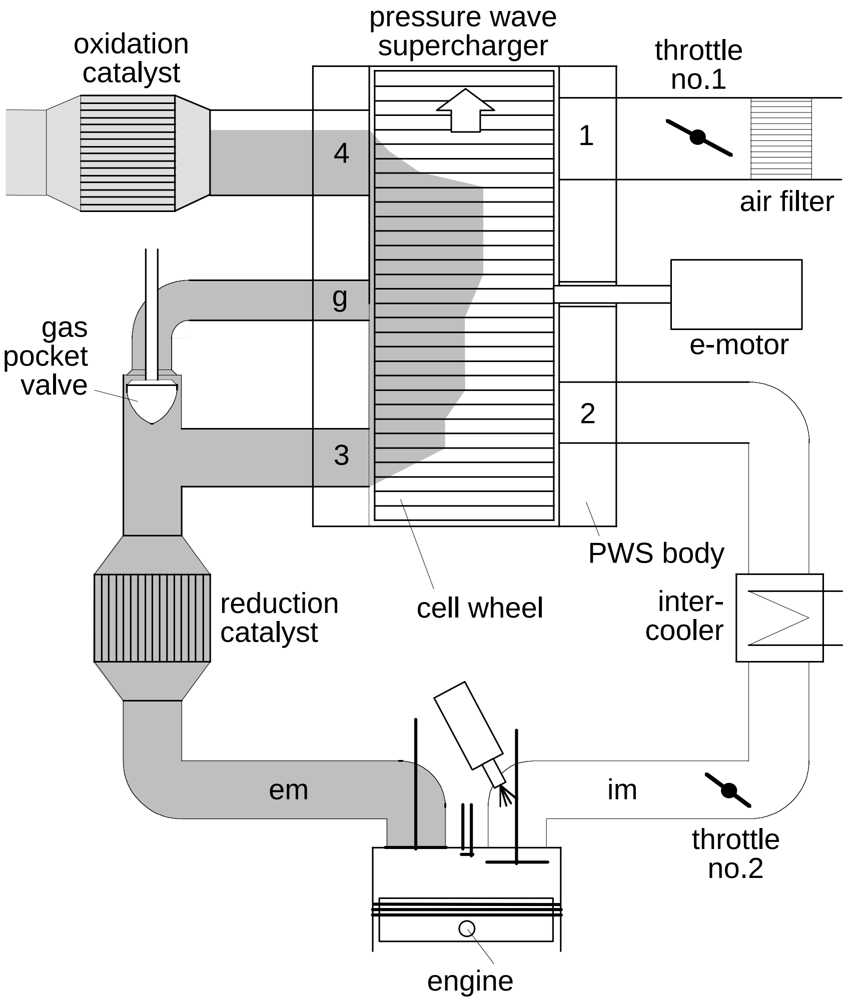
Mean Value Modeling of a Pressure Wave Supercharger including Exhaust Gas Recirculation

Felix Weber



System structure of the pressure wave supercharged SI engine

3.1. Key words

Pressure wave supercharger, gas dynamics, exhaust gas recirculation, control oriented modelling

3.2. Abstract

Naturally aspirated spark ignition engines with three-way catalytic exhaust gas aftertreatment systems inherently show a poor efficiency at part load conditions. Since engine torque is controlled by changing intake manifold pressure, throttling causes pumping losses. One attempt to avoid throttling is engine downsizing and recovering the engine power by supercharging. Compared to a naturally aspirated SI engine a small supercharged SI-engine operates more efficiently in the range of low and middle loads due to minimized pumping losses.

The pressure wave supercharger represents one system of supercharging a downsized SI-engine. The exhaust gases transmit their energy in direct contact to the fresh air. The dynamic boost responds with sonic speed, but undesirable exhaust gas recirculation through the charger is possible. Sudden exhaust gas recirculation causes a breakdown of the engine torque. In order to guarantee good driveability, exhaust gas recirculation must be avoided. The objective of the presented work is to investigate, to model and to explain the effects of exhaust gas recirculation with a pressure wave supercharger.

The work presents a mean value system model of an SI engine supercharged with a pressure wave supercharger with gas pocket valve. The system model is able to predict states such as pressures, temperatures, mass flows, engine torque, and exhaust gas recirculation in steady state and transient operation. It explains why the scavenging process of the pressure wave supercharger during a load step must deteriorate. Model extrapolation demonstrates that a faster closing of the gas pocket valve causes worse scavenging.

The most important part of the overall system model is the model of the pressure wave supercharger. It calculates a simplified pressure wave process based on the relations of the linear one-dimensional gas dynamics neglecting the fast dynamics of the pressure wave process. It is validated by the identification of four physically motivated model parameters. As a result, the non measurable leakage losses of the pressure wave supercharger, the non measurable mixing zone length, and its profile between exhaust gases and fresh air can be determined. The validated model of the pressure wave supercharger shows an error in the order of 5%.

The developed mean value system model of a pressure wave supercharged SI engine is a simulation tool. The tool may be used for system analysis, system optimisation, and model based controller design.

3.3. Objectives of the thesis

The main objective is the development of a mean value model of a pressure wave supercharger which can be integrated as a submodel into an engine system model. In order to simulate the steady-state and the transient operating behaviour of a pressure wave supercharger together with an SI engine, the simulation has to explain the occurrence of exhaust gas recirculation during transients. The modelling approach has to be physically based, control oriented and suitable for an implementation as a real time model in a controller.

3.4. Main results and new contributions

The main contributions of this thesis are

- Description of the pressure wave process of a pressure wave supercharger including steady state exhaust gas recirculation by a physically based mean value model approach. The model calculates the outputs as a function of the measured pressures and temperatures in the channels and of the rotational speed of the pressure wave supercharger.
- Derivation of the non measurable, pressure wave supercharger typical leakage losses out of the cell wheel, the non measurable mixing zone length, and its exhaust gas fraction profile by model parameter identification
- Development of a simulation tool capable of simulating the transient working behaviour of a pressure wave supercharger together with an SI engine including transient exhaust gas recirculation effects. Due to the fact that the simulation tool is a physically based white box approach, the simulation tool can be computed in real time.
- The model study shows the working principle of the gas pocket valve and explains its influence on the pressure wave process.

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Mittelwertsmodellierung eines Druckwellenladers mit Berücksichtigung von Abgasrückführung

Felix Weber

3.5. Zusammenfassung

Otto-Saugmotoren mit Drei-Wege-Katalysator zeigen in der Teillast einen schlechten Wirkungsgrad als Folge der Füllungsregelung. Die Absenkung des Einlassdruckes über eine Drosselklappe führt beim Motor zu Gaswechselverlusten. Ein möglicher Ansatz zur Verbesserung des Teillastverhaltens von Otto-Saugmotoren ist die Aufladung des Motors bei gleichzeitiger Hubvolumenreduktion (Downsizing). Im Vergleich zu Saugmotoren arbeitet ein aufgeladener Ottomotor gleicher Leistung bei kleineren bis mittleren Lasten effizienter, da im Vergleich zu einem Otto-Saugmotor weniger Gaswechselarbeit geleistet werden muss.

Der Druckwellenlader stellt eine Möglichkeit für die Aufladung des Verbrennungsmotors dar. Da im Rotor des Druckwellenladers die Rauchgase und die Frischluft in direktem Kontakt stehen, ist unerwünschte Abgasrückführung über den Lader möglich. Eine plötzliche starke Abgasrezirkulation führt zu einem Einbruch des Drehmoments. Um gute Fahrbarkeit zu garantieren, muss unerwünschte Abgasrezirkulation vermieden werden. Das Ziel der vorlegenden Arbeit ist es, den Effekt der Abgasrezirkulation über den Rotor des Druckwellenladers zu untersuchen, zu modellieren und zu erklären.

Die Arbeit präsentiert ein Motormodell eines mit einem Druckwellenlader mit Gastaschen-Ventil aufgeladenen Ottomotors. Das Modell sagt Zustandsvariablen wie Drücke, Temperaturen, Massenströme, Motordrehmoment und Abgasrezirkulation über den Lader mit guter Genauigkeit voraus, und zwar für stationären und instationären Motorbetrieb. Das Motormodell erklärt, weshalb die Spülung des Druckwellenladers während eines Lastsprungs schlechter werden muss. Die Modellextrapolation zeigt, dass ein schnelleres Schliessen des Gastaschen-Ventils zu einer Verschlechterung der Spülung führt. Der zentrale Teil des gesamten Motormodells ist das Modell des Druckwellenladers. Basierend auf den Grundlagen der eindimensionalen, linearen Gasdynamik berechnet es einen vereinfachten Druckwellenprozess, wobei die sehr schnelle Dynamik des Druckwellenprozesses vernachlässigt wird. Das Modell ist mittels Identifikation von vier physikalischen Modellparametern validiert worden. Damit können die nicht messbare Leckage des Druckwellenladers, die nicht messbare Mischzonenlänge und deren Konzentrationsprofil zwischen Rauchgas und Frischluft bestimmt werden. Das validierte Druckwellenladermodell zeigt einen Fehler in der Grössenordnung von 5%.

Das hier entwickelte Motormodell eines druckwellenaufgeladenen Ottomotors ist ein Simulationswerkzeug. Dieses Werkzeug kann in einem zukünftigen Projekt für Systemanalysen und Systemoptimierungen wie auch für modellbasierte Reglerentwürfe eingesetzt werden.

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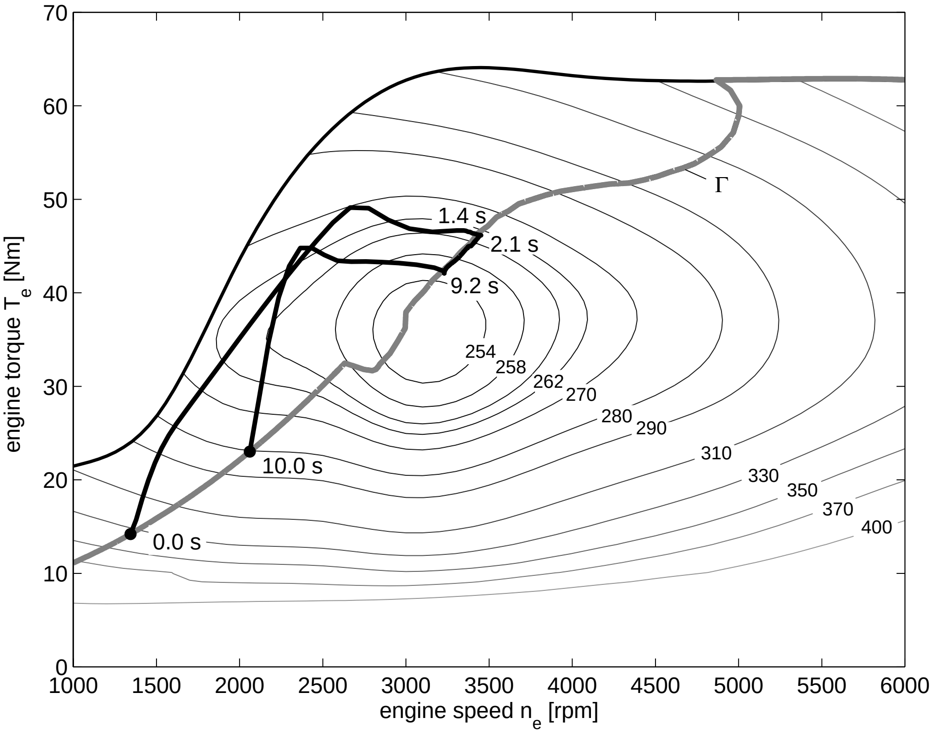
Optimal Operation of CVT-based Powertrains

Rolf Pfiffner



Engine map trajectory of the optimal solution

4.1. Key words
CVT model, CVT efficiency map, single track strategy, optimal control

4.2. Abstract

This thesis analyses the fuel-optimal operation of powertrains that are equipped with a Continuously Variable Transmission (CVT). Although the use of CVT's is commonly considered as a promising approach for the improvement of the fuel economy of passenger cars, the operation mode that achieves minimum fuel consumption is known for stationary vehicle consumption only. For transient vehicle conditions, however, three approaches have been proposed so far. All of them rely on heuristic arguments, and the reasoning for fuel-optimality is based on "quasi static" considerations. A truly dynamic solution is not yet available.

In order to fill this gap, a detailed model of the complete powertrain is developed and a reasonable performance index (cost function) is defined. The fuel-optimal control problem for transient vehicle operation is brought into an appropriate mathematical framework, i.e., it is formulated as a nonlinear optimal control problem which is then solved for various predefined vehicle trajectories using state-of-the-art numerical optimization software.

These investigations are carried out for a representative of the class of lightweight passenger cars. Within these investigations, two different engine types are considered: one is a conventional SI engine and the other is a downsized supercharged (DSC) SI engine. In both cases, the

optimal solutions are shown to be superior to standard CVT control algorithms, yielding larger gains in fuel economy for DSC engines.

The optimal control problem has been solved for various transient vehicle trajectories. Common features of these solutions are identified. They have been used to derive a causal suboptimal control strategy that realizes almost the same benefits in fuel economy, but requires a substantially reduced computational effort. Hence, it is realizable on-line.

On the basis of a comparison between the suboptimal control strategy an the classical control strategy, some adjustments for the classical well-known single track modified control strategy are proposed. The resulting improvements in fuel consumption are similar to those of the suboptimal control strategy.

4.3. Objectives of the thesis

The fuel-optimal strategy for CVT-based powertrains in stationary conditions is the well-known engine operation on the peak efficiency curve for stationary operation. For transient vehicle conditions, however, it is not obvious which trajectory in the engine map will produce the best possible fuel economy for a given vehicle speed trajectory. Objective of the thesis is to find the fuel optimal control algorithm in truly dynamic conditions and to compare it to classical approaches.

4.4. Main results and new contributions

The optimal control problem for transient vehicle operation was formulated and solved for two different engine types: a downsized supercharged engine and a conventional SI engine of approximately the same power. For this purpose new models of the DSC engine and the CVT had to be developed. The new CVT model includes a measured mechanical efficiency map and a gear-type pump model for the hydraulic supply. The equations of motions describing the mechanical part of the CVT were replaced by a new approach. As a result, an overall efficiency map of the CVT was derived, which is a three-dimensional function of the input shaft speed, the input torque, and the gear ratio. Considering the efficiency map, the optimal control for “quasi static” conditions yields some new features: Since the CVT efficiency also depends on the gear ratio, the “quasi static” peak efficiency curve is no longer a single line, but becomes a particular curve for every vehicle speed.

Compared to the best classical control approaches, the expected fuel economy improvements with optimal control are in the range of 3% for the DSC engine, whereas for the conventional engine the best classical strategy is shown to be almost optimal. However, compared to today’s most commonly implemented strategies the fuel economy improvements are approximately 4% for the DSC engine and 6% for the conventional engine.

Deriving common features of the optimal solution, a realizable on-line strategy is proposed achieving the same fuel economy benefits with a substantially lower control complexity.

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Optimaler Betrieb von CVT-basierten Antrieben

Rolf Pfiffner

Zusammenfassung

Das Thema der vorliegenden Arbeit ist der verbrauchsoptimale Betrieb von Fahrzeugantrieben, die mit einem stufenlosen Getriebe ausgerüstet sind. Obwohl die Anwendung von stufenlosen Getrieben als ein vielversprechender Ansatz zur Verbrauchsverbesserung von Personenkraftwagen angesehen wird, ist die verbrauchsoptimale Strategie nur für stationäre Fahrzustände bekannt. Für transiente Fahrvorgänge wurden bis anhin drei Steuerstrategien angewendet, die auf heuristischen Überlegungen aufgebaut sind. Die Grundlage dieser Strategien besteht in der Annahme von „quasistationären" Fahrzeugbedingungen. Die dynamische Lösung war bisher nicht bekannt.

Zur Lösung des dynamischen Problems wurde ein Modell des gesamten Fahrzeugantriebes entwickelt sowie ein sinnvoller Güteindex (Kostenfunktion) definiert. Durch diese Massnahmen konnte das dynamische Problem in eine geeignete mathematische Darstellung überführt werden, d.h. es wurde als nichtlineares dynamisches Optimierungsproblem formuliert. Die Lösung dieses Problems wurde unter Verwendung moderner Optimierungssoftware für verschiedene Fahrzeugtrajektorien berechnet.

Die Berechnungen wurden für einen typischen Vertreter der Kleinwagenklasse durchgeführt, wobei zum einen ein konventioneller Verbrennungsmotor, zum anderen ein hubraumverkleinerter und aufgeladener Motor betrachtet wurde. Die optimale Lösung ergibt für beide Motorkonzepte im Vergleich zu konventionellen Steuerstrategien eine Verbrauchsverminderung. Die Einsparung ist im Falle des hubraumverkleinerten Motors grösser als für den konventionellen Motor.

Anhand der optimalen Lösungen für verschiedene Fahrzeugtrajektorien wurden Charakteristika der optimalen Lösung identifiziert, welche die Herleitung einer suboptimalen Steuerstrategie erlaubten. Die suboptimale Steuerstrategie ist im Gegensatz zur Berechnung der optimalen Lösung in Echtzeit realisierbar, wobei die Verbrauchseinsparung nur marginal abnimmt.

Der Vergleich der suboptimalen Steuerstrategie mit den klassischen Steuerstrategien ermöglichte eine Weiterentwicklung der bekannten single track modified Steuerstrategie. Mit diesem modifizierten Algorithmus können ähnliche Verbrauchseinsparungen wie bei der suboptimalen Steuerstrategie erreicht werden.