Simulation of a COMPREX® Pressure Exchanger
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Good afternoon Ladies and Gentlemen.

This presentation deals with the simulation of a COMPREX pressure exchanger and shows the technique used for the optimization of these devices including the prediction of the pressure-flow rate map.

First, I would like to express my sincere thanks to my fellow co-authors prof. Macek, Dr. Polasek and Mr. Vítek for valuable and inspiring suggestions and advice.
Simulation of a COMPREX® Pressure Exchanger
Presentation Structure

• Introduction
• 1-D Model of a COMPREX® in GT-POWER
• Results and Comparison with Basic Theory
• Improvements to COMPREX and Effects on Operation
• Conclusions

Now, let me outline the structure of this presentation.

As an introduction, I would like to describe how the COMPREX works. Then I will show you the implementation of this device into GT-Power. The results achieved by the COMPREX 1-D model will be compared to a basic shock wave theory of COMPREX. Then I will show you the wave phenomena inside the COMPREX pressure exchanger in more detail.

Finally, I will summarize this presentation.
Aims of this Study

• simulation and optimization of a COMPREX® pressure exchanger in steady operation
• to find tools for optimized-control of pressure exchanger

Ways

• adapt a general-purpose engine simulation tool for this special task
• test the model by simulating a standard COMPREX® pressure exchanger
The COMPREX pressure exchanger was proposed by Brown Boveri & Cie, Baden, today ABB, and ETH Zürich in 50’s as an alternative boosting device using the direct pressure energy exchange between exhaust gas and fresh air.

The pressure is transferred at almost 1-D flow from the exhaust gas to the fresh air in a controlled system of narrow channels.

The flow control is provided by the slide valve gear, created by a channeled rotor between the flanges with appropriate inlet and outlet orifices for exhaust gas and fresh air.

Exhaust gas flows into the rotor and impacts the fresh air in the channel. In this way, the compression pressure wave compresses air and after the air outlet is opened it expels air to an engine manifold.

The rotor rotates, which prevents the exhaust gas from reaching the air outlet orifice and allows it to expand through the exhaust gas outlet orifice into the lower part of the exhaust system.

This exhaust gas expansion provides the suction of fresh air into the channeled rotor through the opened air inlet orifice.
The key component of COMPREX pressure exchanger is its rotor with narrow channels, which connect the orifices in flanges. The original BBC design of 34 channels was changed to double or even triple layered in the late 70’s of 20th century.

The rotor is driven by a V-belt connected to the engine crankshaft, which provides rough synchronization of channel opening and closing.
This picture shows the basic gas dynamic model. At both ends the channel is connected by flow-split elements to the exhaust gas inlet pipe, exhaust gas outlet pipe, fresh air inlet pipe and charge air outlet pipe through the individual orifices. The model was developed for small SI gasoline engines. The rotor length was chosen equal to the rotor diameter.

The size of the rotor and control geometry of flange orifices was first optimized by the method of characteristics to reach the boost pressure of 2 bar at maximum break torque.

The resulting timing is presented for both exhaust gas flange and air flange in the next picture.

Every control orifice is placed twice at the perimeter of a flange, in order to minimize the thermal deformation of a flange. This feature will be used with advantage when constructing the model.
By means of this picture I will explain the use of time dependent orifices in place of the real slide valve-like performance of the flow control.

The control of the first channel is provided by a use of the ActuatorConn template and by use of the Lookup1D template, where the control geometry of the orifice is defined as a function of the time.

The other channels are opened and closed with a certain time delay. This is introduced by the elements Delay connected to the ActuatorConn as well.

By the double symmetrical flange orifice layout the same control function of opening and closing is simultaneously used for two symmetrically placed channels. This can be seen in case of the exhaust gas inlet orifices in the lower part of the picture.

It allows the use of a smaller number of elements Delay, which are limited, and contributes to shortening of computation time.
The standard COMPREX pressure exchanger was driven from an engine crankshaft.

Therefore, the drive was modeled by sensing of crankshaft angle using a SensorConn part and by a variable amplification of its magnitude by Gain element.

Both air and exhaust flange are modeled in a way similar to the plenum of a engine manifold.

The rotor was divided into 12 channels. The number of modeled channels is limited by available number of control elements Delay and by demands on the computation time.

This simplification is not absolute precise, if the interaction between COMPREX and engine in manifolds is considered, but in most cases quite satisfactory.
Results and Comparison with Basic Shock Theory

Basic Shock Wave Theory of a COMPREX® Pressure Exchanger

Exhaust Inlet Orifice

Shock Wave of Pressure Ratio $\pi_3 = \frac{p_3}{p_0}$

Flow-Rate/Pressure-Ratio Dependence

$$m_3 = A_{el} \cdot p_3 \cdot \frac{\kappa \cdot r \cdot T_0}{r_3} \cdot \sqrt{\frac{2}{\kappa}} \cdot \frac{(\pi_3 - 1)}{\sqrt{\pi_3 \cdot (\kappa + 1) + \kappa - 1}}$$

Reduced Flow Rate $\frac{m_3 \cdot \sqrt{T_3}}{p_3}$

We do not have any experiment results, so the rough validation of the simulated results was done by comparison to simple basic shock wave theory of COMPREX.

The simple model of COMPREX you can imagine as a pipe filled in by a initially steady fresh air, in which propagates shock wave of a pressure ration $p_3$ to $p_0$ created by impact of the exhaust gas on the fresh air.

The combination of well-known gas dynamics equations for 1-D flow - that is combination of continuity equation, equation of momentum and energy conservation - yields an equation that describes the exhaust gas flow rate as a function of pressure ratio. This equation assumes there are no friction losses and the boost pressure equals the exhaust gas pressure.

The relation for flow rate can by easily transformed to the reduced flow rate used as a standard form for turbines.
This plot, shown similar to the quantities used in a turbine map, gives the comparison of predicted flow rate characteristics of both models. This comparison is presented for different engine speeds, which changes mass flow rate and appropriate exhaust gas temperature.

The COMPREX speed was optimized to the highest achieved boost pressure at every simulated operation point.

The comparison shows reasonable agreement between both models. The GT Power model shows qualitative improvement caused by throttling and channel friction.
Results and Comparison with Basic Shock Theory

Example of Result Evaluation

Boost Pressure and Exhaust Back Pressure

Since dependence between boost pressure and exhaust back pressure is of interest, this plot presents the maximum break torque speed characteristics of the boost pressure and exhaust back pressure.

Like the turbocharger, the COMPREX pressure exchanger has the region of possible scavenging and region of exhaust gas recirculation.

Unlike the turbocharger, the trend of boost pressure is not quadratic with increasing engine speed, but rather linear. It means that even for a COMPREX, wastegating is advantageous.
Now I will describe the potential of the precise 1-D model. Look at the pressure wave phenomena inside the COMPREX pressure exchanger at the optimal operating point. There is exhaust flange on the left side and air flange on the right side of the picture.

Between the both flanges is placed the channeled rotor. The vertical axis of the time is transformed from the cylindrical cross-section of the air and the exhaust flanges. The solid lines with a slope represent the propagation of the pressure waves in the rotor.

The dotted lines stand for the paths of exhaust gas and air in a channel.

The optimal operating point means the pressure waves are tuned on the flange orifices.

The time of pressure wave propagation depends on the exhaust gas temperature and mass flow and is not proportional to the engine speed.

Therefore, if the COMPREX is driven by constant transmission ratio, the optimum pressure wave roadmap is tuned to the one engine speed only.

Using the simplified COMPREX model and method of characteristic this distance time road map and the control geometry of flange orifices was developed for a boost pressure of 2 bar.

Using GT-Power at maximal torque curve, the engine speed was found at which boost pressure of 2 bar was achieved. In this case it was at 3060 rpm.
This plot gives for the mentioned operation point the comparison of the flow velocity in all orifices for both models.

The comparison of the idealized simulation to reality by 1-D model is shown for both the exhaust flange orifices in the upper part of the plot and for the air flange orifices in the lower part of the plot.

The back flow in the exhaust gas inlet orifice is caused by a reflection of initial compression wave at the wall of the air flange. This exhaust gas back flow causes then the charge air back flow in the air outlet orifice.

This backflow is not shown in the idealized shock wave model, which demonstrates the precision level of the 1-D model and stresses the need for detailed simulation.
We have tried to determine whether the model is capable to predict the influence of pockets.

The pockets are a design solution that improves the function of COMPREX out of the optimum point. The pockets cause bypassing of gas between the channels and control orifices.

The compression pocket prevents the back flow in the high pressure part. The expansion pocket prevents the back flow in the low pressure part. The gas pocket solves the problem of rotor scavenging at low engine speed. The additional admission of exhaust gas into channels amplifies the exhaust expansion wave and improves rotor scavenging.
In GT Power pockets are modeled as additional pipes attached to the channel. The expansion pocket, compression pocket and gas pocket are controlled by time-adjustable orifices in the same manner as in the case of channel control.

The COMPREX model confirmed the positive influence of pockets on the maximum torque curve as can be seen from this plot. At constant engine speed of 3000 rpm the COMPREX speed has been changed and change in boost pressure has been observed. Below the optimal COMPREX speed, the COMPREX with all pockets produces a higher boost pressure than the COMPREX without pockets. Above the optimum COMPREX speed the difference between both models is not appreciable.
I have shown that boost pressure control should be used even for the pressure wave exchanger. In addition to the waste-gate control the variable gas pocket can be used in place of waste-gate.

By the variable gas pocket control the exhaust gas bypasses the high pressure part, but it does not bypass the low pressure part. In this case the exhaust gas supports scavenging of rotor channels, which improves efficiency at high engine speeds.
This picture presents the comparison of both types of boost control, if the boost pressure is controlled at the level of 2 bar. It is obvious that the waste-gate control causes the higher exhaust back pressure than the variable gas pocket control for the same boost pressure.
This picture demonstrates that the waste-gate control strongly disturbs the scavenging of the COMPREX rotor in the low pressure part. 

It causes the increase of exhaust gas recirculation at higher engine speed and decrease of engine torque according to the variable gas pocket control.
## Conclusions

- Implementation of a COMPREX® Pressure Exchanger into 1-D Engine Model
- GT-POWER comprehensive object library is sufficient even for this unusual task
- Good agreement with an algebraic model based on the theory of adiabatic shock wave and at least qualitative agreement with published sources
- By implementing COMPREX® model to GT-SUITE all its features can be fully used

Let me summarize the results of this presentation.

I described implementation of a COMPREX pressure exchanger into 1-D engine model.

The comprehensive object library in GT-Power makes it possible to simulate and optimize the pressure exchanger attached to the engine and is sufficient even for this unusual task.

The results have not been compared to measurement yet. Nevertheless, at least the qualitative reactions of the model are in good agreement with a simple algebraic model based on the theory of adiabatic shock wave and at least qualitative agreement with published sources.

By implementing COMPREX model into GT-SUITE all its features can be fully used especially for simulation of interaction between COMPREX and engine.

Thank you very much for your attention.