Development of a mechatronic transmission control system for a Formula Student drivetrain

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Abstract — The tractive force has to be interrupted during a gear-shifting operation in a manual vehicle transmission, leading into a decrease of speed while changing gears during the acceleration process. Therefore in a racing application, the shifting time has to be as short as possible so that the required performance of a racing car can be achieved. The following paper is a summary of the development of a transmission control system, to enable gear changes within a manual gearbox of a Formula Student drivetrain. To draw conclusions regarding the shifting time and to prove the functionality of the system, an open test bench is constructed. Additionally, the hardware and software is developed to enable the test run. By comparing the achieved shifting time of alternative solutions, an improvement in the driving performance of a Formula Student racecar is probable.

Keywords—Shift-by-wire, Tractive force interruption, Formula Student, Shifting time

I. INTRODUCTION

Various student teams from technical universities compete against each other in the racing series Formula Student. The objective is not only to develop the fastest car, but construction and performance is evaluated as well, taking into consideration the financial planning, and the sales arguments of the teams. The aim of the project is the acquisition of practical experience and application of theoretical knowledge provided in lectures [1].

Corresponding to the objectives stated above, the task of the K71 Project is the development of a specified drivetrain for Formula Student applications. The development is based on the existing K71 engine from the motorcycle manufacturer BMW [2]. The engine was customized by several modifications in order to meet the requirements of Formula Student applications. To take advantage of the modified power unit, the gearbox was modified in order to supply the driving wheels with the required tractive power [3]. During gear changes in the gearbox, the tractive force needs to be interrupted, leading to a decrease of vehicle speed during the shifting time. The discontinuity in the torque flow thus affects mainly the acceleration process [4][5]. Consequently the shifting time will have to be as short as possible, depending on how fast the dog rings can take up their positions. In order to enable shifting operations with the optimized gearbox of the K71 Project, a shifting system is required to position the dog rings.

II. FUNDAMENTAL BASICS OF THE TRANSMISSION

A. Gearbox of the K71 Drivetrain

The gearbox of the K71 drivetrain is a four-gear mesh gearbox. To clarify the function, the gearbox layout is shown in Figure 1.

![Gearbox layout](image)

**Fig. 1.** Gearbox layout: 1: Input shaft; 2: Output shaft; 3: Fixed gears; 4: Loose gears; 5: Dog rings; 6: Clutch

The fixed gears are mounted on the gearbox input shaft. The loose gears are connected to the gearbox output shaft by axial moveable dog rings.

B. Mechanical shifting system

Figure 2 shows an example of a typical sequential shifting system of a six-gear gearbox. The axial movement of the dog rings are enabled by axial moveable selector forks (1), which are controlled by a twistable selector barrel (2). A lever mechanism (4) ensures the positioning of the selector barrel in the required rotation angle, by turning the shifting shaft (5), which reaches outside of the gearbox housing. To hold the selector barrel in the selected position, a locking mechanism is used. A spring (6) moves the shifting shaft in its original position. A toothing structure (7) is located at the end of the
Fig. 2. Standard K71 gear-shifting system: 1: Selector forks; 2: Selector barrel; 3: Sprocket; 4: Leaver mechanism; 5: Shifting shaft; 6: Spring; 7: Toothing

Fig. 3. Principle of the direct pneumatic actuation: A: Neutral position; B: First gear engaged; C: Third gear engaged; 1: Rear mounting; 2: Pair of pneumatic cylinders; 3: Selector fork

Fig. 4. Circuit diagram of the direct pneumatic actuation: 1: Pressure accumulator; 2: Air supply; 3: Pressure gauge; 4: Manual on-off valve; 5: Pressure regulator with gauge; 6: 5/2 way valves; 7: Pairs of double acting pneumatic cylinders

Fig. 5. Test Bench: 1: Pressure accumulator; 2: Compressed air preparation 3: Gear shafts; 4: Selector forks; 5: Valve terminal; 6: Pairs of pneumatic cylinders; 7: Linear potentiometers; 8: Drive; 9: Holes for the circuit board

Fig. 6. Dimensioning of the pneumatic cylinders

By the usage of a pneumatic system, no energy needs to be supplied while keeping the selector forks in their position.

III. SELECTION OF CONCEPT

A. Direct Pneumatic Actuation

A direct actuation of selector forks with pneumatic components was selected as the most feasible concept by means of a utility analysis. For the shake of clarity, only the selected concept shall be described in this paper.

As the actuators are powered by a compressible working fluid, problems can occur in terms of the positioning of the selector forks. Therefore in this concept, two pneumatic cylinders are used to move one selector fork.

Furthermore the energy for the system can be supplied by a pressure accumulator, therefore no energy needs to be supplied by the engine. This is combined by a reduction of mechanical components to transfer the force to the selector forks.

IV. EXPERIMENTAL SETUP

A. Test Bench

An open test bench had to be constructed enable the function testing of the shifting system.

The Figure 5 shows the CAD model of the developed test bench. The construction work was done with the CAD program Catia.

B. Dimensioning of the pneumatic cylinders

To choose suitable pneumatic cylinders, the movement range of the selector forks has to be considered. According to the available CAD data, the selector forks need to move 5 mm in each direction. Furthermore, the pneumatic cylinders must provide sufficient force to connect and disconnect the gear pairs as quickly as possible. As described in Section 2B, the selector
barrel in the standard gearbox gets turned to do a shifting operation.

![Diagram](image.png)

Fig. 6. Forces acting on the selector barrel: 1: Bolt of the selector fork; 2: Selector barrel

The assumed amount of torque on the standard selector barrel is 8 Nm. This value is higher than the measured one on the standard K71 engine. However it can be expected, that shifting operations can be done safer and quicker with more powerful components.

Assuming a force transfer without friction, the torque of 8 Nm can be converted into the necessary force for the pneumatic cylinders, based on the geometry of the selector barrel.

Figure 6 shows the forces acting on the selector barrel during a shifting operation.

The tangential force $F_t$ results from the torque on the selector barrel and the diameter of the point of applied force on the selector barrel. The diameter of the applied force is, according to the CAD data of the standard selector barrel, 49 mm. The tangential force is calculated by the following Equation.

$$ F_t = \frac{2 \times T_w}{d_w} \tag{1} $$

$F_t = 326.5 \, N$

- $F_t$: Tangential force
- $T_w$: Torque
- $d_w$: Diameter of the point of applied force

The force which is moving the selector forks to engage the gears is the axial force $F_a$. This results from the force parallelogram shown in Figure 6 as follows.

$$ F_a = F_t \times \tan \alpha \tag{2} $$

- $F_a$: Axial force
- $\alpha$: Inclination of the selector gate

According to the CAD data, the inclination angle of the selector gate $\alpha$ is 34°. In this way, the axial force can be determined.

$$ F_a = 220.2 \, N $$

As shown, the required piston force is $F_a = 220.2 \, N$. A suitable pneumatic cylinder is the "ADVC 25-5-I-P-A" from the company Festo, which will be used in the shifting system [6].

C. Dimensioning of the pressure accumulator

The energy to power the pneumatic components is stored in a pressure accumulator. Therefore the test bench can be operated without an extern pressure supply. The accumulator has a capacity of two liters; the maximum pressure is limited to 16 MPa. In order to fill the pressure accumulator, the pneumatic connector located at the backside is used.

To show the sufficient dimensioning of the pressure accumulator, the possible amount of shifting operations is calculated. The input parameters for the calculation are shown in Table I.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Symbol</th>
<th>Rating</th>
</tr>
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<tbody>
<tr>
<td>Pressure pneumatic cylinders [MPa]</td>
<td>$p_c$</td>
<td>6</td>
</tr>
<tr>
<td>Piston diameter pneumatic cylinders [mm]</td>
<td>$d_p$</td>
<td>25</td>
</tr>
<tr>
<td>Piston stroke pneumatic cylinders [mm]</td>
<td>$h$</td>
<td>5</td>
</tr>
<tr>
<td>Pressure resistance pressure accumulator [MPa]</td>
<td>$p_A$</td>
<td>16</td>
</tr>
<tr>
<td>Capacity pressure accumulator [l]</td>
<td>$V_a$</td>
<td>2</td>
</tr>
</tbody>
</table>

As shown, the calculation assumes a pressure of 6 MPa to drive the pneumatic cylinders.

The basis for the calculation is the law of Boyle-Mariotte. It states, that the pressure of ideal gases $p$ is inversely proportional to the volume $V$, assuming a constant temperature and amount of substance.

$$ p \times V = \text{const.} \tag{3} $$

In the case of the pneumatic shifting system, two states are assumed. In the first state, the pressure accumulator is filled to its maximum capacity. In the second state, the air escapes completely in a different chamber, where the pressure is $p_c = 6 \, MPa$.

The air volume in the second state needs is calculated as follows.

$$ p_c \times V_2 = p_A \times V_A \tag{4} $$

$$ V_2 = 5.33 \, l $$

The air volume $V_2$ is used to fill all the pneumatic components of the shifting system; furthermore it is used to power the pneumatic cylinders. The air volume to power the pneumatic cylinders $V_c$ is calculated as shown in Equation 5. Simplified just the volume of pressure accumulator is assumed to be filled, as is has a much bigger volume than the other pneumatic components.

$$ V_c = V_2 - V_A \tag{5} $$

$$ V_c = 3.33 \, l $$

To calculate the possible amount of movements with the pneumatic cylinders, the stroke volume of one pneumatic cylinder $V_{c1}$ is calculated.
The possible amount of movements $n_p$ results from the following equation.

$$n_p = \frac{V_c}{V_{cn}}$$

For each shifting operation, two pneumatic cylinders are moved. An exception is the shifting operation from the neutral position to engage a gear and vice versa. Therefore, about 679 shifting operations can be assumed.

The filling of the other pneumatic components, such as pneumatic hoses, valves and the air preparation was excluded in the calculation. However, due to the high amount of calculated shifting operations, the capacity of the pressure accumulator can be considered to be appropriate.

### D. Hardware

The hardware has to provide the necessary components for the data acquisition, processing and the electrical actuation of the valves. This includes components for the input to allow the user to initiate a shifting operation. Furthermore, additional options have to be provided to adjust the settings of the control software. The operator should also be able to access the status data of the system. Another requirement is the monitoring, to protect the gearbox or to ensure the driving stability in case of malfunctions. This also includes components for the processing of the measurement results from the linear potentiometers. To ensure a short shifting time, the hardware needs to operate quickly.

Figure 7 shows the functional architecture of the hardware. The main component is the microcontroller, which executes the software program. Furthermore, integrated storage possibilities allow to save data on the chip. Additional components in the microcontroller enable the connection of hardware peripherals [7] [8].

To actuate the valves, a valve driver is necessary. This component supplies the coils of the valves with the required electric power, as soon as an electrical signal from the microcontroller is received. This is enabled by NPN Darlington pairs connected to a free-wheeling diode [9].

As shown in Section 4A the position of the selector forks is detected by linear potentiometers.

To use the signals from the linear potentiometers in the microcontroller, an analog-digital converter is necessary. The shown functional architecture assumes an analog-digital converter integrated in the microcontroller.

Pushbuttons on the circuit board allow the command inputs "shift up" and "shift down".

LED’s$^1$ are provided for function testing during the development of the control software.

In order to have more possibilities for command input and also to display the operating conditions of the transmission control system, an external computer shall be connected to the hardware. To do so, an RS232 transceiver is used to enable the communication between the microcontroller and the external computer by means of a serial interface [10].

### E. Software

The software has the task to execute shifting operations initiated by the operator. For this purpose, the command input needs to be processed and the positions of the selector forks need to be detected. As only one dog ring can be engaged at one time, it is important to recognize whether a dog ring is engaged or not. Therefore, the voltage values of the potentiometers need to be compared with previous set values, which define whether a gear is engaged or not. On this basis, electrical signals have to be sent to the valve drivers to move the dog rings in the required position. Another important aspect is to provide safety measures and to verify the accuracy of the measured potentiometer values.

It is also important to enable the communication of the shifting system with the external computer. Furthermore, the user should be allowed to change certain parameters of the control system.

Based on the state machine of the software, shown in Figure 8 the basic functions of the control software are explained.

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$^1$Light-emitting diode
After starting the software, the system is waiting for the initialization command (1). The command can be made by the first press of one of the push buttons or by the initialization command on the extern computer. During the initialization (2), the valve coils are energized to move the selector forks in the defined neutral position. Figure 9 shows the positions of the pneumatic cylinders in the neutral position.

After the selector forks (6) are moved into the neutral position (7), the measurement values of the potentiometers are compared with target values, set in the shifting system. Therefore the accuracy of the linear potentiometers can be verified. If the measured values are outside of the range of tolerance (8), the shifting system switches in the error state (3). After a successful initialization, the system state is changed in the waiting mode (4).

In this mode, a shifting operation can be made. Another initialization can be started was well.

A shifting operation can be executed either by a command input on the extern computer or by pressing a push button on the circuit board. This changes the state of the system into the shifting mode (5).

As an example, Figure 10 shows a shifting operation from the first to the second gear.

At the beginning the first gear is engaged (A). This is recognized by the control software due to the measured position of the selector forks. As only one dog ring is allowed to be engaged at one time, the marked selector fork (6)(B) is moved towards the neutral position.

A set threshold value of the potentiometers detects, whether a dog ring is engaged or not (12)(B). As soon as the selector fork passes the threshold value, the opposite dog ring can be moved into the second gear (C).

Another threshold value set in advanced detects, when the selector fork has reached the end position (D). By means of this position, the shifting time can be calculated. In the following step the shifting system is switched in the waiting mode again.

As described above, the software changes in the error mode, when the initialization wasn’t successful. Furthermore the error state is reached, when the maximum shifting time exceeds a certain value. Another shifting operation is impossible in the error state. By means of a successful initialization, the system can be changed in the waiting mode again.

V. EXPERIMENTAL RESULTS

The following chapter shows the test run. The objective is to find out the optimal settings for the test bench. Furthermore the possible shifting time shall be determined under these conditions. The speed of the gearbox input shaft is fixed for the testing.

Therefore changeable settings are the potentiometer values defining, whether a dog ring is engaged or not. The threshold values are set with a certain tolerance. By reducing the tolerance, the shifting time should decrease as the selected gear
can be engaged earlier. However, a reduction of tolerance increases the risk to engage two gear pairs at one time. This can lead to serious damage. A further possibility to influence the shifting time is to adjust the operating pressure. By increasing the pressure, the shifting time should be reduced due to stronger actors. However, by increasing the operational pressure, the energy consumption increases as well. Furthermore, the mechanical stresses of the pneumatic cylinders need to be considered, as the residual energy of the pneumatic pistons in the end positions can damage the actors.

To find the optimal settings for the system, the above mentioned parameters are changed separately. The shifting time can be read from the terminal window after each shifting operation. To collect enough data for accurate test results, the shifting system did five upshifts from the first to the fourth gear and five downshifts from the fourth to the first gear. This results into 30 shifting operations with each setting.

Table II shows the impact of the variation of the operational pressure on the shifting time. During the test, the tolerance of the potentiometers was set to the voltage value of 30. Table III shows the average shifting time while the tolerance of the potentiometer threshold values was changed. The operating pressure for the test was set to 6 bar.

<table>
<thead>
<tr>
<th>Pressure [bar]</th>
<th>Avg. shifting time [ms]</th>
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<tbody>
<tr>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>147</td>
</tr>
<tr>
<td>3</td>
<td>78</td>
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<td>4</td>
<td>73</td>
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</tr>
<tr>
<td>6</td>
<td>62</td>
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<tr>
<td>7</td>
<td>61</td>
</tr>
<tr>
<td>8</td>
<td>61</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Tolerance [ADC value]</th>
<th>Appr. Tolerance [mm]</th>
<th>Avg. shifting time [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>1,3</td>
<td>65</td>
</tr>
<tr>
<td>30</td>
<td>1</td>
<td>62</td>
</tr>
<tr>
<td>20</td>
<td>0,7</td>
<td>63</td>
</tr>
<tr>
<td>10</td>
<td>0,3</td>
<td>62</td>
</tr>
</tbody>
</table>

As shown in Table II, an increase of the operational pressure doesn’t influence the shifting time noteworthy, once the pressure is above 6 bar. The increase of the shifting time below 3 bar can be explained by the operation principle of the valves, which are operating according to the servo principle. To ensure a quick switching of the valves, the pilot air supply shouldn't fall below 3 bar [11].

After reducing of the pressure to 1 bar, the valves couldn't operate timely, which resulted in an overrun of the shifting time set to 1000 ms.

The variation of the threshold tolerances doesn’t have a noteworthy impact of the shifting time. However, increasing the tolerance to any value isn’t useful, as these values would overrun the values of the neutral position.

Due to the measurement results, an operational pressure of 6 bar and a tolerance of 30 is considered to be suitable for the test bench. The expected shifting time is therefore about 62 ms.

Due to the differences of the shifting system on the test bench, compared to the usage in the K71 drivetrain and the differing operating conditions, the shifting time might be slightly different in the drivetrain.

One difference is the weight of the moveable parts of the system, which is higher on the test bench as the parts manufactured from conventional steel. This increases the inertia forces during a shifting operation. Another aspect is the required sealing for the holes of the shifting rods in the drivetrain. These parts are not mounted on the test bench and will increase the friction loss during a shifting operation.

The different operating conditions result from the speed of the gearbox input shaft.

The maximum speed of the gearbox input shaft on the test bench is 256 rpm, whereas the speed of the shaft in the drivetrain will vary mostly between 1554 rpm and 5699 rpm.

These values are calculated from the primary gear ratio of 1.93 and the expected engine speed range of 3000 rpm to 11000 rpm [3].

VI. CONCLUSION

The in this paper, a transmission control system based on a direct pneumatic actuation was developed. The direct actuation enables the positioning of the selector forks without additional mechanical shifting elements inside the gearbox. This reduces friction loss. Furthermore, the mechanical parts would have to be accelerated during the shifting operations and additionally, they add weight to the drivetrain. Another advantage of the pneumatic system is the energy supply, which can easily be stored in a pressure accumulator.

The test run on the test bench, described in Chapter 5, shows an average shifting time of 62 ms. As described, the result does not necessarily reflect the operations in the drivetrain, due to the different operating condition. Nevertheless by comparing the developed system with other concepts, the system can be considered to influence the dynamic driving properties of a Formula Student racing car positively. Firstly due to the low weight of the system which is expected to be about 4.7 kg (CAD data). Secondly due to the fact that the system requires no energy to be supplied by the engine. Assuming a shifting time of about 62 ms in the K71 drivetrain, the developed system would be also beneficial in terms of a short tractive force interruption. Additionally the actuated system is capable of assisting the driver during a shifting operation, being easier to operate than a manual system.
REFERENCES


