1D modelling and PID control of helicopter Diesel engine rotational speed in torque changes

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Abstract. The article discusses the results of simulation tests concerning the operation of a diesel engine for a light helicopter. The tests were carried out in the AVL Boost software which is used to analyze dynamic phenomena in internal combustion engines. The research object was a newly designed diesel engine of a V8 structure and a power of 330 kW. This engine was designed to be used in the construction of a light class helicopter. The created one-dimensional simulation model included all the main engine components as well as the connection to the helicopter main transmission and the helicopter rotor. The tests consisted in selecting the P value in the PID controller used to control the amount of fuel injected into the engine. The change in the P value indirectly influenced the reaction of the engine to a change in power and torque during horizontal flight of a helicopter. These changes were introduced by changing thrust torque in the helicopter rotor. The fuel injection regulator was designed to maintain a constant engine rotational speed. The maximum speed deviations from the nominal speed of the engine operation due to both increasing and decreasing speed were analyzed. Additionally, the sum of the deviation values was analyzed until the rotational speed of the tested object stabilized. The results showed that the change of the P parameter affects all the analyzed parameters of the engine operation; however, the minimum deviation values for each parameter occur at non-equal PID settings, which makes it difficult to clearly indicate the appropriate value of the P element.

1. Introduction
The reduction of fuel consumption and toxic emissions of flying vehicles is now strongly emphasized. One type of widely used flying vehicles are helicopters. One of their main flying area are residents spaces in large agglomeration. Among many ideas for reducing toxic emissions from these aircraft is the use of hybrid helicopters [1, 2]. This solution combines the advantages of an internal combustion engine with an electric motor but its design is a complex issue. At the current stage of technology [3, 4], using a diesel engine in a helicopter as one of the ideas to fit into this trend seems simpler [5, 6]. Currently, the technology of diesel engines for automotive applications is based on electronic injection control. In addition, the use of new materials and technologies reduces the weight of such an engine, which makes it possible to think of using a diesel engine in a light helicopter. Such a solution could bring many advantages like reduced fuel consumption in relation to turbo-shaft propulsion and reduced emission of toxic exhaust fumes into the environment. However, the specific nature of a diesel engine and helicopter operation, cannot not be combined so easily. The helicopter as a complex machine can have certain problems with a stable control of its main rotor. The helicopter has
a very high linear velocity of its blade tips, which should not exceed 0.9 of local speed of sound. Another limitation is ubiquitous vibrations. These affect the flight stability and endurance of the helicopter and the engine [7]. Therefore, certain impassable ranges of rotational speed of the main rotor, and consequently also of the engine powering the helicopter are assumed. It is commonly agreed that main rotor speed should not vary from the nominal value by more than 5% [8]. This, of course, depends on the size, type and design of the helicopter. In some flying units these values are much smaller. Failure to meet these parameters may result in damage to structural elements of the helicopter or its accident [9, 10]. Therefore, so-called passive and active vibration dampers are used in helicopter structures [11, 12].

The requirement to maintain a constant rotational speed also directly affects the power unit, which introduces the need for an appropriate engine control strategy. The compression-ignition unit, compared to the turbo-shaft engine, is characterized by a larger amplitude of vibrations and their different nature, which can also affect the interaction and transmission of vibrations between the helicopter and its engine. However, this is a separate issue.

In this work, the author analyzes a proposal to use a diesel engine to propel a light helicopter. In such a propulsion unit, control is carried out quantitatively by changing the fuel dose [13], which allows a much faster response to the change in the external torque occurring in the rotor of the helicopter which, in turn, is transferred to a rapid response to dangerous deviations of rotational speed from the nominal value. These phenomena can now be analyzed with simulation software. This trend is global [14, 15] and the use of simulation programs to analyze the operation of internal combustion engines saves design and calculation time.

2. Research object

The research presented in this paper is an analysis of rotational speed deviations from a preset constant engine speed. It should be remembered that, in fact, the rotational speed of the engine and the main rotor in a helicopter can change only by about 5%. Exceeding this limit carries the risk of resonant vibrations, which, in consequence, may lead to helicopter damage. The model for the simulation studies was made in the AVL BOOST RT software [16]. This type of software is capable of simulating dynamic phenomena in internal combustion engines and propulsion systems. The model consists of an internal combustion engine, a helicopter gear element and a helicopter rotor.

![Figure 1. Piston engine modeled in AVL BOOST RT](image-url)
The engine consists of eight cylinders arranged in a V configuration and is equipped with a supercharger and a modern Common-Rail type fuel supply system with an electronic control system. Its complete model is shown in figure 1.

The model includes components such as external environmental conditions (Ambient 1), an ambient air pressure of 100,000 Pa and a temperature of 298.15 K. These conditions were not changed due to the fact that light class helicopters reach small flight ceilings, and changes in external conditions will be negligible and will hardly affect engine operation. The engine has a compressor (Compressor 1) that is connected by a rigid shaft. The compressor's compression and speed are directly proportional to the rotor (and engine) torque. There is a time lag of about one second between the change in torque and the speed response of the turbocharger.

The following are the basic data of each of the 8 cylinders:
- diameter: 87 mm,
- piston stroke: 93 mm,
- compression ratio: 16:1,
- connecting rod length: 157 mm.

Adopted as a combustion model in the simulation, a two-zone Vibe model includes the following assumptions:
- combustion start moment,
- type of fuel-air mixture - homogeneous [18],
- fuel temperature in the tank is 298.15 K (25 °C),
- parameters characterizing the heat exchange of the outer cylinder walls and the environment [19],
- types and sizes of inlet and outlet valves,
- inlet valve lift vs. degree of crankshaft rotation,
- airflow coefficient in relation to inlet valve lift.

The model is also equipped with intake and exhaust linkages (Plenum) and mechanical linkages (Shaft). All the main parameters of the engine interior are defined in part (Engine 1), as shown in figure 2.

![Figure 2. Main parameters of the engine model [17].](image-url)
The friction forces that occur in the engine were also introduced into the model and assumed to be directly proportional to the speed of the motor. The engine is connected by a rigid shaft (Shaft 2) to a gearbox (Single Ratio Transmission 1) with a ratio of 8.5 and an efficiency of 98%. The moment of inertia at the input and output of the gearbox is 2 kg\(\cdot\)m\(^2\). The transmission is connected to the helicopter's carrier rotor (Mechanical Consumer 1) with a moment of inertia of 400 kg\(\cdot\)m\(^2\). The last component of the model is a speed controller. It has two functions (Fn 1: TargetSpeedDiff and Fn 2: Fuelling) and consists of two PID controllers (PC 1: OuterWindow and PC 2: InnerWindow). The first function, Fn 1, calculates the difference (control deviation) between the target speed and the current speed and then passes the information about the deviation to the PID controller. The function Fn 2 calculates the fuel injection dose for the next cycle of each cylinder. The new fuel dose is equal to the sum of the dose from the previous cycle and the correction of the PID controller. The algorithm for calculating the fuel dose is shown in figure 3. This algorithm is based on the use of a common rail system in a diesel engine [20, 21].

![Figure 3. Algorithm for calculating the fuel injection rate [17]].(image)

If the speed difference from the first function is greater than 300 rpm, the correction is calculated by the PC 1 controller. If this difference is less than or equal to 300 rpm, the correction is calculated by PC 2. If the speed difference is zero, the function does not take into account the correction of the PID controller in the next cycle. FN 2 passes the injection rate information to the map (GM 1: FuelMultiplierMap) which calculates the injector opening time and passes the information to the fuel system (Mass Flow 1). The main parameters of the PID controller are shown in figure 4.

In the tests, the desired constant speed was set at 3500 rpm. The running algorithm was designed to maintain this rotational speed. The torque change forcing that occurred was due to the horizontal flight of the helicopter. In each successive computational step after turning on the simulation, the simulation conditions stabilized within 5 seconds. The total time was 15.9125 seconds from the time the conditions stabilized. Various settings of the P controller were analyzed from -0.000219 to -0.00069, changes in 0.00001 increments with constant settings of I = -0.0017 and D = 0.
3. Results

The experiments resulted in plotting the speed characteristic as a function of simulation time. The characteristic deviates both positively and negatively from the desired nominal speed of 3500 rpm. An examplary theoretical course of this characteristic is shown in figure 5.

![Figure 5. Example of the rotational speed characteristic.](image)

The so presented courses for each setting of the P value were then subjected to further calculations. First, the sum of the areas under and over the nominal velocity value was calculated as in equation (1).

\[
P_i = \sum_{i=1}^{n} (RPM_i - RPM_{nominal}) \times t
\]

where:
- \(t\) – time between successive engine speed measurements,
- \(RPM_i\) – measured engine speed at a given time,
- \(RPM_{nominal}\) – nominal rotational speed.

In the next step, each \(P_i\) value was related to the minimum value from all calculated \(P_i\) values as in equation (2).
\[ P_j = \frac{P_i}{P_{\text{min}}} \]  

(2)

where:

- \( P_i \) – summed area of differences for a different \( P \) value in PID,
- \( P_{\text{min}} \) – minimum value of all \( P_i \) values.

The absolute values were then calculated from the numbers representing the maximum deviation of the rotational speed from the nominal value, both for higher and lower speed as in equations (3) and (4).

\[ \text{RPM}_{\text{max-nominal}} = |\text{RPM}_{\text{max}} - \text{RPM}_{\text{nominal}}| \]  

(3)

\[ \text{RPM}_{\text{min-nominal}} = |\text{RPM}_{\text{min}} - \text{RPM}_{\text{nominal}}| \]  

(4)

where:

- \( \text{RPM}_{\text{max}} \) – maximum value of rotational speed,
- \( \text{RPM}_{\text{min}} \) – minimum value of rotational speed,
- \( \text{RPM}_{\text{nominal}} \) – nominal value of rotational speed.

The so calculated values were related to the minimum values from the set of their equivalents for different settings of \( P \) as in equations (5) and (6).

\[ \text{RPM}_{\text{max'}} = \frac{\text{RPM}_{\text{max-nominal}}}{\text{RPM}_{\text{max-nominal}}_{\text{min}}} \]  

(5)

where:

- \( \text{RPM}_{\text{max-nominal}}_{\text{min}} \) – minimal value of all \( \text{RPM}_{\text{max-nominal}} \)

\[ \text{RPM}_{\text{min'}} = \frac{\text{RPM}_{\text{min-nominal}}}{\text{RPM}_{\text{min-nominal}}_{\text{min}}} \]  

(6)

where:

- \( \text{RPM}_{\text{min-nominal}}_{\text{min}} \) – minimal value of all \( \text{RPM}_{\text{min-nominal}} \)

All these calculations allowed us to determine the relative deviations \( \text{RPM}_{\text{max'}} \) and \( \text{RPM}_{\text{min'}} \) and the sum of the \( P_j \) deviations. These values are compiled in figure 6.
4. Summary
As can be seen in the graph in figure 6, not all lines reach their minimum values for the same settings of the P member. The P_j curve has the lowest value for P=-0.0003. The RPM_{max'} curve has the lowest value for the value between P=-0.0004 and P=-0.00037. The RPM_{min'} curve has the lowest value for P=-0.00028. Since there is no common point for all minimum values, a compromise on the choice of the best setting for P must be considered. Large deviations from the nominal speed value are most dangerous for operation of an internal combustion engine in a light helicopter so it can be assumed that the most favorable setting will be a P value in the range from P=-0.00036 to P=-0.0028, resulting in a maximum deviation of 1.06. This deviation value is acceptable for a working process of a combustion engine in a light helicopter. The conclusions from this simulation can be useful for further implementation and use of a diesel engine in a light helicopter, which is consistent and in line with the environmental concerns of aircraft use.

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