DELILAH Report Summary

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Final Report Summary - DELILAH (Diesel engine matching the ideal light platform of the helicopter)

Executive Summary:

The optimal diesel engine designed for the light helicopter was assumed to reach an ideal helicopter characteristics and fulfill the environmental impact reduction expectations according to the ACARE goals for year 2020 as defined in the call. The main goal of the project was to defined the optimal turbocharged diesel engine and the integration studies to make use of the engine for the ideal helicopter platform. The results of the project demonstrate a substantial potential for pollutant emission and fuel consumption reduction by powering the light single engine category helicopter with this advanced diesel engine instead of a conventional small turboshaft engine.

Hence, the research and development work in DELILAH was based on the following deliverables:

• Engine Specification - Engine General Description,
• Engine Specification - Subsystems,
• Engine Specification - Thermodynamic Analysis,
• Engine Specification - Engine Vibration Characteristics,
• Engine Specification - Engine Control System,
• Engine Specification - Interface Control Document,
• Environmental impact report.

The technical challenge has been to obtain the power-to-weight ratio taking into account helicopter requirements such as reliability and TBO. An optimal diesel engine has been chosen by selection procedure where ratings criteria will be based on performance, weight, size, fuel economy, emissions, multi-fuel capability, reliability, noise, technology, costs, integration, cooling, and drag. The engine configuration has been selected from the several types of engines. Finally, the engine with the defined engine sub-systems has been designed. To solve the design problems designing tools to design aircraft and automotive piston engines have been applied. The project relates to the solution of problems like: vibration, noise, transmission chain coupling and torque oscillations, engine control and response. To solve these problems, the innovative ideas has been done to develop and analyze the high dimensional dynamics of the multi-body mechanical system and the original diesel engine adaptive control system.

The project of a full authority digital engine controller (FADEC) has been developed. The project includes the fuel injection system and takes into account the numerous variables of the engine with respect to exhaust gas emission, combustion pressure, EGT, torque, and engine speed limits.

To establish the environmental benefits of the diesel engine technologies, mathematical models have been created and the performance and environmental impact of an advanced diesel engine light helicopter have been calculated, incorporating project technology developments. This phase is preceded by an analysis of the flight scenario. The performance of the helicopter is inseparably related to the load at the input to the propulsion system. With an increasing focus on reducing the use of fossil fuel to minimize climate change, there have been performed the calculations using not only usual diesel fuel but also biofuels and biomass-to-liquids (BTL) diesel fuel. The results have shown that the use of biofuels reduces nitrogen oxide emissions but increases soot emission.
Project Context and Objectives:

Main goals of the project
The project defines the optimal turbocharged diesel engine and the integration studies to make use of the engine for the ideal helicopter platform.
The positive results of the project demonstrate a substantial potential for pollutant emission and fuel consumption reduction by powering a light single engine category helicopter with this advanced diesel engine instead of a conventional small turboshaft engine.

Technical Challenge
The technical challenge was tough concerning engine development in particular to reach the power-to-weight ratio taking into account helicopter needs such as reliability and TBO. The engine weight is the crux of the project. An optimal diesel engine has been chosen by selection procedure where ratings criteria will use:
• highest priority criteria: performance, weight, size, fuel economy, emissions;
• middle priority: multi-fuel capability, reliability, noise, technology;
• lowest priority: costs, integration, cooling, drag.

The engine configuration has been selected from among several types of engines (in-line, V, opposed-piston, radial, Wankel) and cycle types (two-stroke or four-stroke). The V-8 engine has been defined as the optimal configuration.

Major project stages
I) Optimal Diesel Engine Specification
The optimal diesel engine design (picture A) for the light helicopter was assumed to reach ideal helicopter characteristics and fulfill the environmental impact reduction expectations according to the Acare goals for year 2020 as defined in the call. This phase was preceded by an analysis of the flight scenario.

1. Technology Analysis
All in-depth survey of available aviation and automotive sources were conducted to identify new developments which offer potential benefits to a helicopter engine. The technology base includes the definitions of:
A. existing automotive diesel technology, extrapolated to the expected level in the 2010s,
B. existing and extrapolated helicopter engine technology,
C. on-going diesel aircraft engine developments.
These technologies were evaluated and ranked according to performance and adaptability (WP1).

2. Engine Design
The technologies which have been chosen as a result of the evaluation and ranking process will be applied to the design of the around 320 kW engine. Performance, stress, weight, and cost calculations were made concurrently (WP2, WP3, WP4),

With the data base the engine performance was analysed for the selected representative group. The diesel engine Weight/power ratio for engines analysed were compared. The major engine construction assumptions were defined in WP1.
The calculations were done under the following ISA conditions: 0, 2500, 4000 and 6000 m. The engine performance obtained is given below. It demonstrates that the engine power obtained is higher than required (WP2).
The engine main components were designed and tested in terms of their strength and fatigue. The input data necessary to analyse stress come from WP2. According to the project requirements, the engine components TBO, which was defined in call for proposal have been consider.
This study determined the geometry of the main components of the crank-piston engine under design, i.e. piston, connecting rod, and crankshaft. The generated structure of these elements and selected materials can ensure the engine to withdraw maximum load and provide safe, long-term, and efficient engine performance (within a given TBO for the engine for full engine
II) Engine/Rotorcraft Integration Study
This study (picture B) was conducted to evaluate the integration of the proposed optimal diesel engines into helicopter. The engine and its subsystems were built on the ideal platform which requires the following connections:
a) thermodynamic – study of the engine heat transfer to the engine bay, cooling and ventilation methods (WP 5),
b) mechanic - the levels of vibration and methods for its reduction (WP 6), and thus how to fix the engine,
c) electronic – definition of the engine control system and its integration in the helicopter electrical and avionics system (WP7, WP8),
d) hydraulic and pneumatic - the integration of the fuel system, cooling, air supply, engine exhaust systems on the helicopter (WP9).

Finally, the design of each sub-system, i.e. a fuel system, cooling system, oil system, electrical system, air inlet system, anti-icing system was determined.
The CFD analysis included the examination of the pressure, temperature and flow distribution for the cooling system and inlet system to determine the optimal conditions for heat transfer between engine and its environment. The cooler design and method of ventilation of the engine bay were developed.
Geometric and dynamic parameters for the engine anchorage points were determined. The MD Adams was used to model this engine and its anchorage points. The study was for the rated speed of the crankshaft, including the piston forces due to heat release.
As a result, the optimum fulcrums for the engine were specified, the main parameters (stiffness and damping) of sensitive elements were selected and the ranges of dangerous frequencies were specified.

III) Environmental Impact Analysis
To establish the environmental benefits of the diesel engine technologies, mathematical models have been created to predict the performance and environmental impact of both, the classic turboshaft and advanced diesel engine light helicopter, incorporating project technology developments. Some parts of models were used to determine the effect of the engine on its operating costs. The results were then compared with the corresponding data for the currently produced turboshaft engine to power light rotorcraft (WP10, WP11, WP12). This model has been used in the Technology Evaluator, along with fleet forecasts for the Year 2020+, so that the Technology Evaluator can assess the environmental benefits of the project technological breakthroughs.
On the basis of the flight scenarios in WP10, the maps of the fuel consumption, maps of emission of toxic compounds of exhaust gases and tables specifying all these parameters during particular flight scenarios have been created. On the basis of the data from the above tables, all four flight scenarios were compared in terms of the emission of toxic compounds of the exhaust gases and the fuel consumption.
In the calculations of the emission of toxic compounds of exhaust gases, a similar method as in the case of the calculations of the fuel consumption was applied. For the thermodynamical model of the engine, the emission of toxic compounds of exhaust gases such as: CO, Nox has been calculated.

Project Results:
The activities of DELILAH project were organised by adopting a Work Package (WP) list and Deliverable (D) list (see table 1 and table 2)
The main scientific and technical results achieved in the project are summarised below.

WP1: Optimal diesel engine technology analysis
Duration - Planned: 2 months - Realized: 2 months

Main Objectives:
1. Developing the methodology to select the type of a diesel engine for helicopter propulsion.
2. Specifying the optimal configuration of the diesel engine for helicopter propulsion.

Description of work:
Task 1: Database development
Task 2: Optimalisation calculation

The main objective of WP1 was to develop a database with the basic parameters of commercially available diesel engines. The database specifies cylinder arrangement, engine power, weight, fuel consumption, etc., and the possible ways to modify engine performance. The next step was to develop the optimization tools which determine the optimal design of the helicopter diesel engine. The applicant applies his own software, i.e. Statistica and Mathematica. The multicriteria optimization was performed to find an optimal solution, acceptable by all the defined criteria. Each criterion had its own assigned importance which was selected to obtain the ideal helicopter characteristics, i.e. take-off weight between 1200 and 2000 kg operating up to 6000 m above sea level and temperature between -40°C and +35°C. The ideal characteristics of the helicopter was determined by modelling the flight scenario. The objectives developed were transferred to the teams that were working on WP1 and WP2.

Results achieved:
During the realization of this WP1 it was necessary to:
• determine the scope of engine main dimensions, i.e. piston stroke, cylinder diameter, connecting rod length,
• determine cylinder configuration,
• determine the scope of crankshaft rotational speed,
• determine the scope of basic indicators for engine operation.

While determining preliminary design parameters, it was also considered that an aircraft propulsion unit should meet several requirements, including:
• low design weight,
• power to be provided under flight conditions projected at the minimum fuel consumption,
• high reliability and operational vulnerability.

A cause-and-effect diagram to express the relations among causal factors which have an impact on the quality of this engine is given in Figure 1 (see attachment).

The basic engine configuration consists of:
• number of cycles,
• cylinder configuration,
• number of cylinders,
• main engine ratios,
• compression ratio,
• Mean piston speed,
• engine operation indicators,
• cooling system,
• charging system,
• lubrication system.

In the database the engine performance was analyzed for the selected representative group. The diesel engine Weight/power ratios for engines analyzed are compared in Figure 2 below (see attachment).

The performance of diesel internal combustion engines was modified in terms of:
• a design of basic elements and material solutions,
• algorithms and procedures to control an engine,
• a fuel supply system,
• an air supply system,
• an exhaust system,
• ways to reduce power and heat losses.

Additional comments:
The most significant results of this task are:
1. The required engine power was determined.
2. The basic engine configuration was determined.
3. The latest technologies used in diesel engines were analysed.
4. A summary of the inevitable minimum additional requirements to be satisfied by a diesel engine installed in a helicopter.
5. A matrix of decision variables developed to be the basis for the research outline in WP 2.
6. The required TBO was obtained.

WP2: Engine working cycle modelling
Duration - Planned: 3 months - Realized: 3 months
Main Objectives:
Analysis of engine thermal and mechanic loads.
Description of work:
Task 1: Developing an engine dynamic model (a single-dimensional model and CFD model)
Task 2: Simulation research
To complete WP3, the applicant used the AVL BOOST software that is a tool for examining engine performance and developed the single-dimensional engine model defined by the team dealing with WP1. Each of the structures analysed was evaluated by a feasibility study in terms of the possibility to modify engine performance (power, torque, fuel consumption). Based on the tests, the guidelines for the possibility of the effective modification of engine performance in terms of thermodynamics (changes in a compression ratio, charging pressure, etc.) was determined. The engine model allowed for variable environmental conditions caused by helicopter flight conditions (flight altitude, cruising speed, hovering). Additionally, the forces that operate on individual engine elements were specified based on the time course of torque as a function of crankshaft rotation. The data obtained was transmitted currently to the team responsible for WP3. The next step was to do the AVL FIRE model research of cylinder filling and combustion. The AVL FIRE software is multi-purpose thermo-fluid dynamics CFD software with a particular focus on fluid flow handling applications related to internal combustion engines. The applicant determined the value of the engine thermal load and calculated the time courses of cylinder induced pressure and heat evolution. The results obtained were transferred all the time to the team working on WP2.

Results achieved:
The AVL BOOST modelling of the diesel engine design for helicopter propulsion was done. The model of the engine in AVL BOOST is given in Figure 3 (see attachment).
The analysis covers:
• the impact of rotational speed,
• the impact of compression ratio,
• the impact of air-fuel mixture composition.
The calculations were done under the following ISA conditions: 0, 2500, 4000 and 6000 m. The engine performance obtained is given below. It demonstrates that the engine power obtained is higher than the required one (Figure 4 – see attachment). The fuel injection and combustion in the chamber was modelled to determine thermal loading that impacts on the engine piston. The simulation was done with the AVL FIRE software based on Computational Fluid Dynamics. The distribution of temperature, speed, and injected fuel stream inside the chamber, as well as the course of temperature, heat release rate and heat transfer coefficient were obtained in the simulation. The temperature and droplets distribution in the cross section of the combustion chamber (360 CAD) is given in Figure 5 (see attachment).

Additional comments:
Based on the conclusions in WP1, the 1D diesel engine model in the AVL BOOST software was developed. Had done and interpreted, the simulations focused on how engine performance could be impacted by the changes in those parameters.
Then, the main engine operation parameters such as engine speed, compression ratio, Air/Fuel Ratio were selected to meet the requirements for any diesel engine mounted in a helicopter. Additionally, the installation of a flat plane and cross plane crankshaft was analyzed; and a latter one was selected. The course of the cylinder pressure was developed to test the strength of the elements of the crank-connecting rod system in WP3.

The 1D model was applied for the 3D modelling of injection and combustion in the AVL FIRE software. The engine working process was analyzed to check the piston thermal loading. The course of HTC was also developed to calculate the piston thermal stress.

WP3 Engine design:
Duration - Planned: 3 months - Realized: 3 months
Main Objectives:
Specifying the basic construction parameters for the diesel engine to power the helicopter.
Description of work:
Task 1: Strength and fatigue analysis
Task 2: Engine weight and installation
Task 3: Engine analysis including TBO

The vibration analysis was performed to check the engine design as defined in WP1. Using the software listed in Chapter 1.2.1 the WP3 team used the values of the mechanical and thermal loading to do the strength analysis of the crank-piston system and engine body. The calculations in Abaqus verified the strength of engine individual components to thermal, mechanical and fatigue loads. Catia V5 was used for designing. The team cooperated with the team working on WP2 to do the task. The team also analysed the installation of the engine in the helicopter in terms of the size of the engine designed. The strength and fatigue calculations helped to specify the required time between overhauls (TBO).

Results achieved:
WP3 entitled “Engine design” determined basic design parameters for a diesel engine dedicated to power a light helicopter. The engine main components were designed and their strength and fatigue were tested. The input data necessary to analyse stress came from WP2. According to the project requirements, the engine components TBO must be more than 4000 h. This study determined the geometry of the main components of the crank-piston engine under design, i.e. piston, connecting rod, and crankshaft. The generated structure of these elements and selected materials enabled the engine to withdraw the maximum load and perform in a safe, long-term, and efficient manner (within a given TBO for the engine for full engine service life).

This geometric modelling was done with the use of CAD (Computer Aided Design) and FEM (Finite-Element Method) using CATIA V5 and Abaqus. Figure 6 (see attachment) depicts the stress distribution in the connecting rod head, big end and cover at the maximum compressible force.

The stress calculation determined the basic design parameters of the diesel engine dedicated to the light helicopter. The dimensions of the crankshaft, connecting rods and pistons were determined. The materials to meet strength criteria were selected. The operating time of individual elements of the crankshaft-piston assembly is higher than it had been assumed in the project proposal (4,000 h). The time of 12,500 hours is the minimum number of hours for the piston and at the upper oil point as it was calculated in the fatigue simulation.

Additional comments:
The optimal configuration was chosen. The performance achieved is consistent with the requirements specified in the call for papers. The overall efficiency of the engine was 44%.

WP4: Definition of all engine subsystems
Duration - Planned: 6 months - Realized: 6 months
Main Objectives:
Specifying the design requirements and solutions for the subsystems.
Description of work:
Task 1: Analyses of the optimal cooling system, oil system, electrical system, fuel system, inlet air dedusting system, anti-icing system
Task 2: Optimal engine to transmission synchronization system and optimal engine cold/hot/ in the flight starting system

WP4 was a comparative analysis of the design, the operating principle and efficiency of the engine subsystems, including its starting system, inlet and outlet system, lubrication system in terms of their proper operation in the helicopter. The modelling was applied to compare the performance parameters of the individual subsystems. The models were developed in FLUENT and AVL FIRE. The WP4 contractors have been experienced in using this type of software for R&D. The research results were related to the requirements enumerated in the report on Deliverables 1. There were also specified the guidelines to control a cooling system, depending on flight conditions. The comparative analyses and modelling calculations specified basic parameters of each subsystem. The final stage was designing all the subsystems of the diesel engine mounted in the helicopter.

Results achieved:
1. Cooling system was determined:
   • Coolant fluid was chosen,
2. Oil system was determined
   • Main components in the lubricant system were determined (oil pump, scavenge oil pump, oil filter, regulator valve, pressure sensor, cold start valve, piston cooling jet, venting the crankcase),
   • Engine oil specification was determined,
3. Electrical system was determined (electricity generating device, internal reciprocating engine starting system, electric starter, electronic on-board battery, alternator, battery), (Figure 7 – see attachment),
4. Inlet air dedusting system was determined,
5. Anti-icing system was determined,
6. Fuel system was determined (design, fuel tank, low pressure fuel lines, fuel filtration system, low pressure supply pump with its pressure regulator, fuel temperature sensor, high pressure pump, fuel rail, fuel flow limiters, fuel pressure regulator, fuel pressure sensor, fuel injectors, high pressure fuel lines), (Figure 8 – see attachment),
7. Inlet system was determined, (Figure 9 – see attachment),

Additional comments:
No comments

WP5: Study of the engine thermodynamic specification
Duration - Planned: 4 months - Realized: 4 months
Main Objectives:
Specifying the heat transfer between the diesel engine and the helicopter engine bay.
Description of work:
Task 1: Analysis of engine heat radiation
Task 2: Heat transfer to the engine bay
Task 3: Optimal cooling and ventilation method

The data obtained in WP2 and WP3 in the 6th month of the project to describe the primary cooling system and the thermal engine specification for the helicopter engine bay defined the characteristic entities required to develop the thermal model of the engine. The range of radiation values from the diesel engine was determined based on a number of experimental studies carried out using a thermal imaging camera. Infrared radiation was registered by the Flir ThermaCAM S65 thermal imagining camera. The next research stage determined the boundary conditions to simulate the engine bay heat transfer in the helicopter. The important step in this task was defining fire protection procedures (fire walls, a fire extinguishing system) which are required for a helicopter design as indicated in the CS-E and CS-27. The conditions of cooling and ventilation of the
diesel engine in the helicopter were determined according to the analysis of the results of the previous tasks. The opportunity to use a helicopter rotor race to cool the engine bay was considered. The entire simulation of the cooling system (air, water, oil, fuel) was done with the use of CFD (Computational Fluid Dynamics). The unit that runs the project owns software like Ansys Fluent, AVL Fire and was experienced enough to operate it. The CFD analysis included the examination of the pressure, temperature and flow distribution of:
• all engine liquids (oil, water, fuel),
• air surrounding engine structure
to determine the optimal conditions for heat transfer between engine and its environment.
Results achieved:
At the beginning the engine thermal testing was made based on the results of the AVL BOOST 1D engine model. The energy balance of the engine operating at maximum power conditions, temperature and pressure at sea level was done. Then, a simulation of engine cooling jacket was made (Figure 10 – see attachment).
The next step was to define the radiators. The calculation of the working surface dimensions of the radiator was started by creating an analytical model of heat transfer in a liquid-air heat exchanger. The construction of the radiator was assumed. In addition, the oil cooler, fuel cooling system and intercoolers were determined.
The adjusting coolant temperature system was also determined (Figure 11 – see attachment).
The next step involved the study of the thermal emission in the engine. The thermal sources were determined on the infrared camera measurements of a turbo diesel engine mounted in the vehicle. The results enabled the assumptions for model calculations of the exhaust heat shield. Then, the geometry of the heat shield of the exhaust system was examined and the heat radiation and heat shield cooling were simulated (Figure 12 – see attachment).
The last step was to determine the fire precautions to satisfy the CS-E 130 regulations.
Additional comments:
No comments

WP6: Engine vibration analysis
Duration - Planned: 7 months - Realized: 7 months
Main Objectives:
Analysing the vibration generated by the engine and developing a method to reduce it.
Description of work:
WP2 and WP3 provided basic information about the object (the main components of the vibration system: crankshaft, other rotating masses and main shape and mass of the helicopter as well as the various speeds and engine components subsystems, etc.). Using these data, the first step of investigation was performed which is the frequency and multibody analysis of the whole system. As a result, the applicant built a simplified model with concentrated masses by means of the MS Adams software in with non-linear equation. This analysis demonstrated the areas which are exposed on fairly large vibration amplitudes and possible dynamical couplings between different masses. The nonlinear effects including nonlinear synchronization, and vibration localization were also studied. Finally, the results of the analysis provided the conditions in which different resonances could occur.
One of the important task was to determine the diesel engine coupling to the rest of the subsystems. It should be emphasised that the characteristic diesel engine frequency is usually lower as compared to the turboshaft engine frequency in existing constructions. In our case, the engine frequency changed as a function of engine load. This investigation enabled the appropriate powerplant system to be selected.
The spectrum of nonlinear system determined the frequency, the size and nature of the interaction between the elements considered. To identify the system dynamics, the applicant also analyzed the corresponding time series obtained in the measurements and simulations using nonlinear methods. Besides the formal Fourier analysis, the applicant applied the wavelet analysis that enabled simultaneous analysis in time and frequency domains. This method allowed us to identify the time scale of changes in the stationary and non-stationary signals.
Recurrence plots and recurrence quantification analysis was used to classify the dynamics of short time series. On the other
The statistical and multifractal analyses helped determine and compare the complexity of the system on the basis of the range (and bandwidth) of the characteristic exponents of corresponding time series. Similar information was provided by the multiscale entropy distinguishing the correlations in the noisy time series. Based on the nonlinear system identification, the efficient method of vibration reduction besides mechanical damping in the form of additional masses and damping elements was developed by using a control algorithm assumptions of fuel injection in transient states, which was used in D5.

Results achieved:
The simulation studies to test how a diesel engine for a light helicopter impacts on a structure of its installation has got two stages. Besides gravity and inertia forces of the rotating or reciprocating elements, the engine is impacted by the force generated by the pressure due to burning a fuel dosage. An incorrectly balanced crank-piston system and a cyclic working stroke in each cylinder can influence the generation of forces that move from the crankshaft to the cylinder block. Then, these forces are transferred to the anchorage points and the structure of the helicopter. Therefore, it was attempted to minimize the amplitude and frequency of the power generated, and thus reduce engine vibration. First, engine vibration was specified. Using the Abaqus software, it was attempted to determine the frequency of crankshaft vibration. This study indicated some dangerous areas for a helicopter propulsion system (see Figure 13 in attachment).

Second, geometric and dynamic parameters for the engine anchorage points were determined. The MD Adams was used to model this engine and its anchorage points. The study was for the rated speed of the crankshaft, including the piston forces due to heat release (indicated pressure) (see Figure 14 in attachment).

As a result, the optimum fulcrums for the engine were specified, the main parameters (stiffness and damping) of sensitive elements were selected and the ranges of dangerous frequencies were specified.

Additional comments:
No comments

WP7: Global FADEC design
Duration - Planned: 4 months - Realized: 4 months
Main Objectives:
Developing the structure of a FADEC including the diesel engine control system.
Description of work:
Task 1: Input and Output Signals definition
Task 2: Integration with avionics and electrical systems definition
Task 2: Warning and emergency study (FADEC) definition
Due to the characteristics of a diesel engine, its control is different from that of a turbine engine. Diesel engine control requires precise control algorithms to ensure crankshaft constant rotational speed, and thus ensure a change of rotor speed no higher than ± 5% rpm, and provide the required power. The first step was determining the necessary measurement signals, control signals and key control procedures (STOP, IDLE, FLIGHT, Fuel Metering, Communication) with cockpit controls and systems (ARINC 429, etc.). Additionally, the WP contractors clarified the issues of avionics control. A FADEC was designed to ensure that specific fuel consumption is minimized. Finally, the diagnostic, emergency and safety procedures were developed. Additionally, a solution that allows a flight to be continued if the FADEC system fails was provided. The control system modelling tests that were done for WPs10-12 were based on such a FADEC system.

Results achieved:
General information about FADEC, including advantages and disadvantages of this system was described. The main issues about the helicopter – engine integration with respect to FADEC signals were discussed. FADEC requirements were described as specified in the CS-E 50 and AMC E 50 regulations. The report describes the new modern technologies to control engine systems in vehicles with Diesel engines and in helicopter turbine engines. The rotor speed control was another important issue
dealt by means of adaptive diesel engine control, including PID controllers. The main idea of this control in the helicopter diesel engine is shown in the diagram in Figure 15 (see attachment).

This step was followed by determining the sensors in the Diesel engine and the parameters that were monitored during different parts of the flight. The sensors, i.e. rotational speed sensor, pressure sensor, airflow meter, temperature sensor, oxygen sensor used in this engine were comprehensively described. The last step was to describe the principle of the FADEC system operation during different stages of Diesel engine operation (Start engine, Idle speed, Warm up, Flight, Auto Rotation, Engine Stop).

Additional comments:
No comments

WP8: Engine control design

Duration - Planned: 3 months - Realized: 3 months

Main Objectives:
Defining the propulsion system control models for a Diesel engine-based helicopter.

Description of work:
Task 1: Simulation research on the control system and control algorithm
Task 2: Simulation research on the control system automatic calibration

If a propulsion system is to be highly efficient, a control process is required to undergo a multiparameter optimization, depending on flight conditions. Any control system must allow for all types of conditions that occur in helicopter operation. The primary change related to supply voltage (about 14.5 V for vehicles), the actuators and measurement elements of the Diesel engine. It was therefore necessary to specify new static and dynamic correction characteristics of these devices, which was completed on the applicant’s test stand. Diesel engine control is multi-dimensional, unlike that of a turbine engine. The basic criterion adopted was to maintain a constant value of rotor speed enabled determining the impact of the control of, e.g. injection time, injection start angle, the number of injection phases or engine boost, EGR and DPF. The simulation research was done using the AVL BOOST software. It was necessary to test various methods of the predictive control of dynamic systems which were used to determine the optimal method by comparing the control error. By defining the control system model, the contractors also took into account the impact of quality control on the composition of the exhaust gases that were emitted by the engine.

Results achieved:
This report specifies how to control the fuel injector at a 28V supply voltage while maintaining the same load at a 14.5 V supply voltage and provides the research results obtained on the bench. Unlike turbine engine control, Diesel engine control is multi-dimensional. The basic criterion was to maintain a constant value of rotor speed. The modelling in AVL BOOST involved determining the impact of regulation of, e.g. injection time, start injection angle, number of injection phases or degree of supercharging the engine. It was necessary to test different methods of predictive control of dynamic systems to later determine the optimal method by comparing the control error.

The engine system analysis done under this task included as follows:
• thermo-gas-dynamic processes,
• ignition and combustion processes,
• mixture formation processes,
• transmission of mechanical energy.

Additionally, a simulation model of control system models was developed in AVL BOOST RT. This control model and modelling were the final result.

The task resulted in fuel injection control procedures necessary to obtain the required engine speed stability. Any further testing of the algorithms defined was carried out in the subsequent tasks.

The master input and output signal in the control system is shown in Figure 16 (see attachment).
WP9: Engine/helicopter study
Duration - Planned: 8 months - Realized: 8 months
Main Objectives:
1. Developing the methodology to select the type of a diesel engine for helicopter propulsion.
2. Specifying the optimal configuration of the diesel engine for helicopter propulsion.
Description of work:
The mounted engine required to be connected to the helicopter systems by means of interfaces. They could be mechanical, electrical, hydraulic, and IT. The first step was to determine the mechanical connections between the engine and the mechanical power receivers (main gear, drive of the units, including the Electric Power Generation).
In order to use the Diesel engine, a clutch connecting the engine and the gear was needed to be developed. It was also necessary to design a damper of torsional vibration that is generated by the crankshaft. Connecting the engine to an electric generator enabled appropriate operation during overload (200 A for 2 minutes; 250 A for 15 seconds). The team dealing with WP9 developed the recommendations concerning the electric bundle connections such as the standard MIL. It was also important to adapt the engine inlet and outlet system mounted in the helicopter. Referring to the IT interfaces, the contractors defined what kind of information the power pack needs to send to the avionics. They also specified the basic information package passed on to a pilot, including hour fuel consumption, or the information on engine technical conditions.
Results achieved:
The connection between the helicopter and the engine were determined:
• mechanical connection between the start system/electricity generation system and the power unit,
• mechanical connection between the helicopter propulsion system and the drive unit (construction, clutch parameters, torque angular frequency),
• electrical interfaces (regulations – standards, adapters, wires),
• IT interfaces (ethernet connection),
The next step was to describe and choose information communicated to the pilot. It was necessary to chose and describe the signals that refer to:
• Combustion Pressure in the cylinder,
• Head Coolant Temperature,
• Coolant Flow Meter,
• Oil Temperature,
• Oil Pressure,
• Fuel Temperature and Fuel Pressure,
• Coolant Level Meter and Oil Level Meter,
• Engine RPM, CMP,
• Intake Air Pressure, Intake Air Temperature, Intake Mass Air Flow,
• Air Pressure Before Turbo,
• Exhaust Gas Temperature, Oxygen Sensor.
The last step in this WP was to describe the exhaust system of the engine. The intake system is described in the D2 report. Report D3 describes the exhaust system with a free exhaust outlet. The exhaust muffler is an alternative solution. The results of noise simulation in the engine exhaust system are given below in Figure 17 (see attachment).
Additional comments:
No comments
WP10: Helicopter cruise modelling  
Duration Planned: 5 months - Realized: 5 months  
Main Objectives:  
Developing the test flight scenario which became the input parameter in the model developed in the WP11.  
Description of work:  
The flight scenario model and the resulting load on the helicopter Diesel engine were developed here. The flight scenario had several basic elements of flight such as engine starting, warming up, idling, ascending and the related change in ambient temperature and pressure, constant speed flight, landing, etc. This was inseparable from obtaining the adequate thrust of the master and tail rotor, and hence the load on the engine shaft.  
Results achieved:  
The flight scenarios were designed. This WP discussed three flight scenarios along with the division into several typical manoeuvres during these flights. Each of the scenarios contains 34 separate different helicopter manoeuvres. For each of these manoeuvres, the temporal percentage share in respect to the total flight time was determined. Additionally, average power required for performing each of these manoeuvres was determined. This power refers to the engine power required to perform a particular manoeuvre by the ideal helicopter. The value of power was determined in percentages in respect of two power characteristics: TOP (Take Off-Power) and MC (Maximum Continues Power). Additionally, there were determined height ranges on which particular manoeuvres were performed.  
To calculate the requirement for power in the conditions of particular manoeuvres in all flight scenarios, the TOP and MC Power characteristics obtained from the simulation calculations were employed. Figure 18 depicts a percentage comparison of the times of consecutive manoeuvres in the three flight scenarios.  
Additional comments:  
No comments

WP11: Dynamic operation diesel engine modelling  
Duration - Planned: 6 months - Realized: 6 months  
Main Objectives:  
Verifying the control system in transient states, defined as a function of changeable shaft load.  
Description of work:  
The mathematical model of the control system was developed in Matlab Simulink. The main input parameter was the engine load defined in WP10. The other input parameters covered the characteristics of the sensors and actuators (quantity estimation errors), the speed and precision of control system response to external changes measured by engine shaft load.  
The output parameters of the model were entered into the thermodynamic engine model developed in WP12 as the time series of fuel injection time.  
Results achieved:  
The task was based on the AVL Boost RT software which was applied to analyze the parameters of the engine operation in dynamic states. To reflect the Diesel engine operation in a light helicopter, the simulation model of this engine based on the same assumptions as used in the previous reports needed to be created. To determine an appropriate control strategy for the Diesel engine mounted in the light helicopter, a series of simulations was performed. These simulations aimed at the optimization of the fuel injection control process according to a change in the required power expressed by a change in the torque on the main rotor. This was achieved by introducing varied values of forcing in the element simulating the main rotor. Two PID regulators were applied to control the engine and ensure the required power and the torque occurred. This control relied on the appropriately selected values of settings of the PID regulator elements depending on a change in the Diesel engine speed with respect to the nominal value of the crankshaft rotational speed. Figure 19 (see attachment) illustrates the consecutive cases referring to the quantity of change of the torque from the lowest to the highest level.
In the calculations, not only the engine crankshaft rotational speed was analyzed but the rotor rotational speed was measured as well. The difference between these speeds results from a selected gear ratio of the main gearbox. Nevertheless, its run in the case of the forcing with alternating torque is similar. The data obtained in the simulation calculations can be presented in the graph to illustrate the relationship between the size of the deviation of the main rotor rotational speed and discrete forcing of the change of the torque.

Additional comments:
No comments

WP12: Environmental impact evaluation
Duration - Planned: 3 months - Realized: 3 months
Main Objectives:
Calculation of the total emissions of toxic components and CO2 based on the thermodynamic model.
Description of work:
The thermodynamic model of the engine developed in AVL BOOST in WP3 was supplemented by the parameters obtained in WP10 and WP11. These parameters include the injection time, temperature, ambient conditions, ambient pressure, engine mechanical load, etc. The output parameters of the model are the emissions of toxic components and fuel consumption. The model was validated against the information provided by the engine manufacturer. The results of the emissions of the toxic components of a piston and turbine engine were compared in the research. As WP 9-12 were carried out, the control algorithm was improved to minimize fuel consumption and toxic component emissions. The calculations were performed for usual fuel LHV = 42800 kJ/kg (Kerosene) as well as biodiesel, biodiesel blends and synthetic biomass-to-liquid (BTL) diesel fuel.
Results achieved:
To calculate the fuel consumption, the characteristics of power as defined in WP10 were applied. These characteristics and the thermodynamical model of the engine designed in the AVL BOOST software enabled the calculation of the fuel consumption for 42 characteristic points of the engine operation. These points were selected proportionally in the range of power and the flight height. The Diesel engine in the light helicopter can be supplied with numerous fuels, including: Diesel fuel; B10, B20, B50 biofuel, B100; Jet A and Jet A1 fuel; or other fuels based on kerosene. It was decided to calculate the fuel consumption and the emissions of toxic compounds of exhaust gases for Diesel fuel and BioDiesel B100 fuel. These two cases were compared by applying BMEP as a constant value which resulted in achieving the same power. Despite the increased requirement for fuel when B100 fuel was used, the criterion for obtaining the same power was adopted due to the necessity to obtain the performance of the helicopter. The calculation of the fuel consumption for the characteristic points was followed by applying higher-order mathematical functions to create precise fuel consumption maps.
The calculations of the emission of toxic compounds in exhaust gases were based on a similar method which had been applied in the calculations of the fuel consumption. The emissions of toxic compounds of exhaust gases such as: CO, NOx, Soot, CO2 were calculated for the thermodynamical model of the engine. All of these components were determined in two units: [g/s] and [g/kWh]; and all of the calculations were also carried out for two types of fuel. The next figure shows CO emission [g/kWh] for B100 fuel.
With the flight scenarios specified in WP10, the maps of the fuel consumption and maps of emissions of toxic compounds in exhaust gases, there were created the tables specifying all these parameters in each of the flight scenarios. On the basis of the data from the above tables, all four flight scenarios were compared in terms of the emission of toxic compounds in exhaust gases and fuel consumption.
Statistical data taken from literature enabled the comparison of the emissions of toxic compounds in exhaust gases and the fuel consumption in the Diesel engine and turbine engines.
Additional comments:
No comments
Potential Impact:
Description of the potential impact:

When helicopter designing was significantly developed in the second half of the 20th century, the turboshaft engine for its better power-to-weight ratio (kg / kW) became a dominant driving unit in this type of aircraft. In the past century, the Diesel engine was not so competitive in terms of this ratio as compared to the turboshaft engine. The disadvantage of turboshaft engines is their dramatically decreasing efficiency with increasing altitude. Their another disadvantage is the necessity to apply a large reduction gear to reduce main rotor speed to about 250-300 rpm. The developing technology at the end of the last century enabled the automotive industry to rely on Diesel engines which are innovative and advanced in terms of construction and control. Currently, the automotive industry is using Diesel engines whose power-to-weight ratio approaches the value of 0.8 kg/kW. The fact that Diesel engines have their mass much larger than turboshaft engines is the most serious problem. If this type of engine is installed in the helicopter, the following technical requirements need to be satisfied:

a) high priority criterion: engine performance, engine weight, engine size, fuel economy, emission of toxic compounds in exhaust gases;

b) medium priority criterion: capability of using varied types of fuels, reliability, noise level, possibility of technological accomplishment;

c) low priority criterion: production costs, operating costs, etc.

This project Diesel engine design had to meet certain requirements. For example, a 330 kW take-off power, estimated from the turboshaft engines used today, needed to be achieved for a light helicopter. It was also necessary to solve the problem of mounting and controlling this engine in a helicopter. Its mass needed to be relatively small whereas its power considerably high. It had to be a turbocharged unit though significantly thermodynamically and mechanically loaded. Therefore, the optimization of components like a piston, a connecting rod, etc. and the selection of materials that could satisfy such adverse conditions were indispensable. All of these requirements related to a Diesel engine have been satisfied and described in this project.

Designing the engine based on the solutions typical of passenger cars and installing it in a light helicopter is beneficial. The most important benefit of using a Diesel engine to drive a helicopter has been significantly reduced fuel consumption and thus the reduction of emissions of toxic compounds compared to today’s turboshaft engines. The advanced technology to control an injection system has also enabled the even greater reduced emissions of toxic compounds and noise generated by an engine.

To compare the emissions of toxic compounds of exhaust gases and the fuel consumption of the Diesel engine and turbine engine, there were used the statistical data. We collected approximate data concerning the fuel consumption and the emissions of toxic compounds of exhaust gases in helicopters which are in common use. A few models of helicopters that have a similar power of the engines to 330 kW were selected. We compared their fuel consumption and emissions of toxic compounds of exhaust gases for a one-hour operation of engines with the power sufficient for Cruise Power flight. A helicopter with this innovative Diesel engine uses at least twice less fuel than the one with a turbine engine. The emission of toxic compounds from our engine in one-hour flight is lower (CO - 20 times, soot - 229 times, CO2 - twice).

Additionally, this engine design enables alternative fuels such as B100 to be supplied, which will contribute to a lower consumption of conventional fuels and a lower emission of greenhouse gases.

This innovative technology will contribute to the improvement of the environment, which corresponds to the EU horizontal policy. The project has a neutral impact on the policy of equality as specified in Art. 17 of Council Regulation (EC) No 1083/2006. The results of this project will lead to the improvement of the environment as specified in Art. 16 of Council Regulation No. 1083/2006. The EU policy aims to protect and improve the environment. The development scenario by the EC Directorate-General for Energy and Transport assumes a 23% share of substitution of petrol and diesel oil in 2020.
As specified in the EU strategic documents (Corinne Hermant-de Callataÿ, Christian Svanfeldt: Cities of tomorrow - Challenges, visions, ways forward, European Union, 2011) related to the plans of EU programmes for 2014-2020, it is necessary to reduce energy sensitivity and CO2 emissions by programmes that could launch new technologies capable of a significant reduction of greenhouse gas emissions. Nowadays, there are too many examples of public transport infrastructure that has caused urban spatial segregation and uncontrolled urban development, increased traffic in city centers and thus CO2 emissions and pollution, and consequently deteriorated the quality of life.

As transport is continuously increasing, the higher share of diesel engine-based helicopter transport of passengers or commodities will be obviously really beneficial. This solution can significantly lower the cost of helicopter flight per hour because fuel consumption is much lower. The cost of diesel engine-based helicopter flight can be further decreased thanks to a less complex construction of such a drive unit compared to a turboshaft engine, which means cheaper maintenance and TBO repair. Lower transport costs will enhance transport development, and consequently economic development. Significantly reduced transport costs will be reflected in household savings as prices of any products are closely related to costs of transport.

Russia as the second largest global exporter of helicopters after the United States exports 99 helicopters per year, worth € 2.5 billion. In 2012, Eurocopter sold 475 helicopters and its turnover reached € 6.3 billion. This type of helicopters is 33% of the global fleet of helicopters of civil use and public organizations.

Concluding, the helicopter industry can depend on Diesel engines in the future, which can be supported by the availability of increasingly lighter structural materials of similar or even better strength than those used today. Consequently, engine weight can be reduced. In addition, some environmental activities to reduce pollution by aircraft and economic benefits from Diesel engine operation in a light helicopter can contribute to the applicability of this type of driving unit.

PhD students’ involvement in this project has also contributed to the development of European young scientists (human resources rejuvenation criterion). While implementing the project, a doctoral dissertation has been started. The project involved 25 people with a total of 224 person-months, which has reduced the unemployment rate to some extent and helped develop the R&D sector.

Dissemination activities and the exploitation of results are given bellow:

The project website with the main project information and news was continually available while the project was implemented: www.delilah.pollub.pl

Also, the information on this project was available on the website of Lublin University of Technology: http://en.pollub.pl/en/international-relations/international-research-projects-and-lut/
delilah-diesel-engine-matching-the-ideal-light-platform-of-the-helicopter

The information on the project was published in the Lublin University of Technology Newsletter: http://www.pollub.pl/files/4/attachment/Biuletyn3%2828%292011.pdf

The project scientific results were disseminated in seminars and workshops across Europe:
4. Joint Meeting „Green RotorCraft ITD” held in the office of the Clean Sky Joint Technology Initiative in Brussels (Belgium), 30 May 2012.
5. 3rd Annual Review Meeting of the Green RotorCraft ITD held in France, Marseille, the Eurocopter Office, 31 May 2012.

The project team started to collaborate with the Universidad Politécnica de Valencia and developed the collaboration with the Universite d’Artois - Bethune (France) and research centre CRITT M2A (France). This will be contribute to the development of
Moreover, the implementation of the project was accompanied by numerous technical and consultative meetings with the representatives of the teams involved in the project and the representatives of AgustaWestland – PZL Swidnik S.A. who were supervising the project as representatives of the Clean Sky consortium.

The project information was published in local and national newspapers as well as websites:

Lublin University of Technology researchers begun their project on the innovative Diesel engine for the helicopter
http://lublin.com.pl/artykuly/pokaz/19973/lublin,naukowcy,z.pl,rozpoczeli,prace,nad,innowacyjnym
silnikiem,diesla,do,smiglowca/

Poles work on a new engine for a helicopter
-smiglowcow

Scientists from Lublin will develop an innovative aircraft engine
,1,4906976,region-wiadomosc.html

Lublin University of Technology scientists carry out their study on an engine for a light helicopter
-smiglowca.html

Super engine for helicopters will be built

Innovative engine developed by Lublin University of Technology

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Related information

| Result In Brief | An eco-friendly helicopter engine |
| Documents and Publications | final1-publishable-summary.pdf |

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