LIGHT WEIGHT PROPULSION SYSTEM DEVELOPMENT FOR UAVs

C.L. Dhamejani*

Abstract

UAV has established itself as one of the major force multipliers for many applications of various armies throughout the world. These UAVs employ different kinds of machines as propulsion systems. Both the Reciprocating and Rotary engines are the leading contenders amongst these machines.

Performance parameters like power to weight ratio, specific fuel consumption and the limited number of requirement of UAV engines call for a development methodology very specific to these engines. Related aspects of development methodology and proving of a modular series of single, twin and four cylinder two-stroke engines indigenously developed for UAV are reported in the paper. Technologies so developed for said series of UAV engines are presented in this paper. Endurance tests as well as limited trials conducted with airframe are also included. Grey areas as foreseen in the indigenous development technologies of rotary engines have been brought out.

Introduction

Today IC engine has penetrated into each and every walk of our life and UAVs are no exception. Initially the number of UAVs flying with IC Engines was not very large, therefore, the engines were not tailor-designed but were modified from the existing ones i.e. from chainsaw and motorcycle application. Propulsion requirements of UAVs such as high specific power output could easily be met by the two stroke power machines. However, constraint on these machines in respect of power to weight ratio has led to ab-initio design development of Rotary piston engine specifically suited to meet the propulsion requirements of UAVs.

This paper is a report on efforts made by the Defence Research and Development Organisation (DRDO) team to configure an engine from the available two-stroke commercial engines. Commercial two-cylinder, two-stroke engine is generally inline type as it uses a clutch and gearbox to transmit the power. Such a configuration is not adaptable by UAV as it uses propeller directly flanged to the engine without the gear box. For such a requirement opposed twin cylinder layout is the optimum. This paper reports the conversion of commercial two-stroke inline engine to opposed firing for UAV application. As the Rotary type of engine is much lighter and more economical to operate, compared to reciprocating type, development of such an engine is considered efforts worthy for light weight propulsion system, as revealed at the end of this paper.

Present Scenario of UAV Engines

Literature survey suggests that power units used for propulsion of UAVs are either of Reciprocating piston or Rotary type. Reciprocating piston type have opposed configuration with two cylinders for 25 hp or a four cylinder type modular construction for 40 to 50 hp range. Corresponding Rotary type engine develops 30 to 40 hp of power with single rotor and the power gets multiplied with number of rotors. Specification of some UAV engines manufactured abroad are given at Table-1 at the end of paper. Certain observations which can be made form the literature are as follows:

Power

Piston engines in the range upto 80-100 hp follow two stroke cycle with petrol lubrication system, whereas beyond said power, four stroke cycle with forced lubrication system is followed.

Speed Range

Operating speeds of UAV engines lies in the range of 7000 to 8000 RPM. Propeller is directly mounted on the engine. Propulsion system with engine can be pusher or
puller type. In some cases reduction drive is applied when the propeller is matched for low speed operation in the range of 4000 RPM.

**Power to Weight Ratio**

Power to weight ratio of Rotary engines lies in the range of 0.5 to 0.6 kg/hp. Generally these engines have 4 stroke type cycle. Reciprocating engines upto the 100 hp range weigh about 0.4 kg/hp and follow two stroke cycle, whereas, larger engines follow 4 stroke cycle and weight about 0.6 kg/hp.

**Fuel Consumption**

Generally the fuel used for reciprocating as well as Rotary engines is Gasoline having a high octane rating of 93 and above. Rotary engines have a fuel consumption in the range from 320 to 380 g/kwh whereas, two stroke reciprocating type consume in the range of 430 to 480 g/kwh.

Keeping these parameters in view, a two-cylinder, two-stroke engine has been developed indigenously for a UAV application. Details of its development, its upgradation and extension of technology to develop a four-cylinder engine is entailed in succeeding paras.

**Two-Cylinder Engines for UAV by Change of Firing Sequence**

**Configuration**

Small UAV’s upto 120kg weight are generally equipped with two-cylinder 2-stroke 20-22 HP engine. Commercially available engines in this range are twin cylinder inline with a phased firing in cylinders at 180º of crankshaft rotation. This design is not very convenient for UAV applications from size, weight and power to weight ratio point of view. Two cylinder engine design in phased firing is inline as against opposed cylinder layout in case of simultaneous firing of cylinders. This requires redesigning and changing the firing sequence from phased firing to simultaneous firing of both the cylinders. This simplifies the design and layout of the engine. To achieve this, crankshaft of the engine was redesigned. Two designs of crankshafts shown in Fig.1 and the corresponding crankcases for the two-cylinder engines so developed are shown in the, Fig.2 and Fig.3 respectively. However, cylinder block, piston and connecting rod remain common for both the configurations (phased and simultaneous firing) of two-cylinder engine.

Thus, twin cylinder opposed configuration using block (175cc) and head from existing commercial engine could successfully be tailored from inline. Twin-cylinder inline commercial engine and Twin cylinder opposed cylinder engine for UAV application are shown in Fig.4 and Fig.5 respectively. Layout of twin cylinder opposed cylinder engine is given at Fig.6. However, weight and life cycle of such an engine was on higher side as compared to existing UAV engines. Therefore following improvements were carried out on the engine.

**Power to Weight Ratio**

Power to weight ratio could be brought down considerably by change of firing order from ‘phased’ to ‘simultaneous’ of the two-cylinder engine. Yet, the commercially available components (piston, cylinder block and cylinder head) in the country are heavier than those used for UAV applications abroad. Therefore, there was a need to develop lightweight components indigenously.

**Assembly of Two-Cylinder Light Weight Engine**

Crankshaft, Cylinder block, Cylinder head, and connecting rod etc. were developed for light weight two-cylinder engine Cylinder block so developed was hard chrome plated single piece pressure die cast (Fig.7) as against with liner which was available earlier. FEM analysis of connecting rod is shown in Fig.8. Engine so assembled with new crankcase and crankshaft using lightweight components is as shown in as shown in Fig.9. Performance of this engine was quite compatible with contemporary engines.

Having established the technology of development of two-cylinder, two-stroke engine, a four-cylinder, two-stroke engine was also developed using the components like piston, block and cylinder head as developed for two-cylinder engine. Design and development details are presented in succeeding paras.

**Design and Development of Four Cylinder Engine**

Design of four cylinder engine in this class posed yet another problem in development of crankshaft. Design of crankshaft comprises of two crankshaft developed for two-cylinder engine. Firing in four-cylinder is achieved so as to fire two cylinders simultaneously and the subsequent two at a phase difference of 180º of crank rotation for best dynamic balancing of engine. Design of crankshaft and its assembly is shown in Fig.10 and FEM analysis is shown in Fig.11. Layout of four-cylinder engine is shown in
Fig.12. Other important features and specific parameters of indigenous four-cylinder engine so developed are quite in tune with contemporary engines available globally. The photograph of assembly of four-cylinder engine with propeller is shown in Fig.13. Performance details of these engines are discussed in subsequent paragraphs.

Performance Evaluation

On Dynamometer

Performance tests of engines were carried out on dynamometer test bed. Four-cylinder engine develops 38 - 40 hp at 6500-7000 rpm. The photographs of dynamometer test set-up are shown in Fig.14. The performance curves of two-cylinder and four-cylinder engine observed on dynamometer are given at Fig.15. The combustion pressure and crankcase pressure measured on engine analyser is given at Fig.16 and Fig.17.

After completion of various tests on dynamometer, the engine was equipped with 30” x 22” propeller and mounted on test bed with cantilever type mounting. Running-in of engine was carried out at part throttle condition at engine speed of 3500 to 4000 rpm. During this run, observations regarding the behavior of engine with reference to the noise, vibration etc were made and nothing abnormal was observed. After running-in, 50 hrs endurance run as per Joint Air Regulation, Section 22 (JAR 22.1849) with propeller fitted were carried out, to prove the reliability of engine.

On Thrust Cradle

A suitable cradle was designed, developed and fabricated to measure the thrust developed by the engine fitted with propeller. A test set-up was developed to measure the thrust of two-cylinder and four-cylinder engine fitted with NP 6972 - 30” x 22” and thrust measurement was carried out using thrust cradle. The test set-up of thrust measurement is shown in Fig.18. The observations of thrust measurement of two-cylinder and four-cylinder reciprocating engines are given at Fig.19.

On Thrust Cradle at CTF

After thrust measurement at VRDE, the engine was subjected to altitude test at ‘Climatic Test Facility’ (CTF). The aim of this test was to study the effect of various altitudes and temperatures conditions on thrust developed by the engine and to measure various engine parameters and ascertain the engine behavior at high altitude and low temperature conditions. A suitable test set up was created in side the climatic test chamber and the engines were tested from 2000 feet altitude to 14000 feet altitude. Four-cylinder engine was also tested up to 14000 feet altitude at sub-zero temperature from -1ºC to -11ºC. Thrust measurement set-up for ‘Climatic Test Facility’ are shown in Fig.20. The observations of thrust measurement at CTF at different altitudes are given in Fig.21.

Vibration Measurement

The vibration levels measured on the engine during initial development phase, when tested on the engine test bed were very high. The maximum vibration levels measured were 12g. During analysis it was realized that these vibrations were due to the eccentricities generated by the crank shaft design, which was developed by joining the two subassemblies by a spline joint. The vibration levels while testing the engine on the engine dynamometer and with the propeller as the load were brought down to 5 to 6g by redesigning the crankshaft with interference fit with liquid nitrogen.

Vibration levels on thrust cradle were 2 to 3g. The vibrations transmitted to the thrust cradle were on higher side initially. Vibration levels were reduced to 0.75 to 1.80g from 2 to 3g by using suitable shock mounts desired for these engines (Fig. 24). The shock mounts were used between the thrust cradle and the engine mounts.

The vibration level inputs to the design team was in great help to have an insight of the engine and to rectify the design flaws and achieving the final goal of producing an engine which is suitable for the intended aerial application.

Having developed the technology of two and four cylinder engines, the modularity of the components was extended to single cylinder engine, which has also been developed successfully and is undergoing extended endurance tests. Description of engine is being withheld due to space restriction.
Integration of Propulsion System with Air-Frame

After completion of various performance and thrust measurement tests, an altitude test stand/frame suitable for two-cylinder engine was developed to test the performance of the engine under actual altitude for short duration. This is a twin boom configuration mainly comprising of Fiber Glass’ rectangular shape partition type fuselage, tail booms and carbon reinforced FRP wings. It measures about 3.4 meters in length and has a wingspan of 6.7 meters. The all up weight of UAV is 70 kg. The maximum speed 120 KMPH and the cruise speed 70 KMPH could be achieved with a two-cylinder engine.

Airframe also has an undercarriage fitted with tricycle wheels with coil spring suspension for easy take-off and landing the vehicle. The Air vehicle electronics includes data logger, flight control electronics, power supply system, Global positioning system and video transmitter. The electronic system is shown in Fig.25 and Fig.26. The photograph of the Arial Vehicle integrated with two-cylinder engine is shown in Fig.27 and Fig.28. The vehicle take-off is conventional and launching by taking-off from a runway prepared at ”National Center for Automotive Testing” (NCAT), VRDE, Ahmednagar.

While two-cylinder engine could be subjected to flight trials successfully, four-cylinder engine is yet to be integrated with an airframe and subjected to flight trials requires a suitable airframe for conduct of flight trails.

Looking at the world scenario on UAV engines, it is noted that further optimisation of engine performance parameters in UAV applications is possible by use of Electronic Fuel Injection (EFI) system. Four-stroke engines performance can also be improved by use of EFI system. Rotary Engine normally operating with four-stroke cycle also performs better with EFI system. Literature survey supported by experiments indicate that performance with EFI system is superior to that of carbureted version in respect of fuel economy and power unit of the engine.

Development of Rotary Engine

Possible configurations rotary engine are Single rotor and Twin rotor engine for UAV applications.

Development of Rotary piston type engine comprises of realizing the components and configuration of single rotor and twin-rotor engine shown in Fig.29 and Fig.30 respectively. Test set-up with Single rotor engine on dynamometer and on thrust cradle are shown in Fig.31 and Fig.32 respectively. Important parameters of single rotor engine as generated on dynamometer are shown in Fig.33. Thrust measurement of single rotor engine is given in Fig.34.

Grey areas in the case of Rotary engine are realizing the components, assembling the engine and performance evaluation. Prototyping will depend upon how good is the finish of components, how well it has been assembled and matching of various systems etc.

Role of EFI System and Future Developments

Two stroke engines are prone to fuel losses accompanied by scavenging. This loss can be controlled to some extent by use of Electronic Fuel Injection (EFI) system. Four-stroke engines performance can also be improved by use of EFI system. Rotary Engine normally operating with four-stroke cycle also performs better with EFI system. Literature survey supported by experiments indicate that performance with EFI system is superior to that of carbureted version in respect of fuel economy and power unit of the engine.

Conclusion

Design and development and prototyping of UAV engine involves optimum configuration and careful realizing the components so as to achieve best performance parameters like weight, fuel consumption, power, speed, vibration levels. Performance evaluation of engine under simulated altitude conditions on thrust cradle can save time for development cycle of engine. EFI system is already used on 2-stroke UAV’s. Final debate between Two-stroke Vs Rotary engine for UAV application will depend upon how successful is EFI in both these applications.

Acknowledgements

Author is thankful to the Director, Shri R.C. Sethi, VRDE, Ahmednagar for permission for publishing this work. Author is also thankful to the team members (not possible to mention names due to limited space) of the establishment for directly or indirectly associated with the work, contributions made by them.

References

### Table-1: Specification of UAV Engines

<table>
<thead>
<tr>
<th>Sl.No.</th>
<th>Engine Model</th>
<th>H.P./RPM</th>
<th>VOL CC</th>
<th>Weight. (Kg)</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ARROW GT 250</td>
<td>34/6800</td>
<td>250</td>
<td>26.0</td>
<td>O</td>
</tr>
<tr>
<td>2</td>
<td>ARROW GT 500</td>
<td>66/6800</td>
<td>500</td>
<td>36.0</td>
<td>O</td>
</tr>
<tr>
<td>3</td>
<td>HIRTH 27</td>
<td>36/5500</td>
<td>438</td>
<td>32.8</td>
<td>O</td>
</tr>
<tr>
<td>4</td>
<td>ARROW GP1000AC2</td>
<td>100/6800</td>
<td>996</td>
<td>63.5</td>
<td>O</td>
</tr>
<tr>
<td>5</td>
<td>ARROW AE530AC</td>
<td>65/6300</td>
<td>533</td>
<td>41.0</td>
<td>O</td>
</tr>
<tr>
<td>6</td>
<td>NORTON P-73</td>
<td>33/5700</td>
<td>207</td>
<td>14.5</td>
<td>R</td>
</tr>
<tr>
<td>7</td>
<td>NORTON P-80</td>
<td>40/6000</td>
<td>294</td>
<td>18.0</td>
<td>R</td>
</tr>
<tr>
<td>8</td>
<td>UEL AR612</td>
<td>125</td>
<td>-</td>
<td>39.0</td>
<td>R</td>
</tr>
<tr>
<td>9</td>
<td>UEL AR682R</td>
<td>120</td>
<td>-</td>
<td>42.6</td>
<td>R</td>
</tr>
<tr>
<td>10</td>
<td>UAV AR801</td>
<td>51/8000</td>
<td>294</td>
<td>24.4</td>
<td>R</td>
</tr>
<tr>
<td>11</td>
<td>WANKEL LCR407 SGti</td>
<td>35/6000</td>
<td>407</td>
<td>25.0</td>
<td>R</td>
</tr>
<tr>
<td>12</td>
<td>WANKEL LCR814 SGti</td>
<td>75/6000</td>
<td>814</td>
<td>35.0</td>
<td>R</td>
</tr>
<tr>
<td>13</td>
<td>RPI 2013R</td>
<td>340</td>
<td>-</td>
<td>193</td>
<td>R</td>
</tr>
</tbody>
</table>

O - Opposed layout engine,  
R - Rotary type piston engine

---

**Fig.1**  Crankshaft of inline and opp. layout engine

**Fig.2**  Crankcase of inline two-cylinder engine

**Fig.3**  Case of opp. layout two-cylinder engine

**Fig.4**  Inline motorcycle engine

**Fig.5**  Modified engine for UAV

**Fig.6**  Layout of twin-cylinder engine
Fig. 33 Performance of single rotor engine

Fig. 34 Thrust measurement of single rotor engine