Acoustic characteristics of aero internal combustion engines

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Abstract. This paper provides a brief overview of internal combustion engines’ noise generating mechanisms. Spectral, energy, and spatial characteristics of the sound field of internal combustion engines used in aviation as part of power plants of light aircraft and unmanned aerial vehicles are considered. The influence of load and flight conditions on the engine noise is considered. An example of the calculated noise estimation of a single-cylinder four-stroke engine is presented. The main methods of reducing internal combustion engine noise are formulated.

1. Introduction
Currently, internal combustion engines (ICE) are used as propeller drives for light propeller aircrafts and unmanned aerial vehicles (UAVs), while providing a low fuel rate and a long flight time.

In contrast to electric generators[1, 2], ICE generate significant noise during operation. Its role in the aircraft community noise depends on different parameters [3]. When designing light propeller aircrafts and UAVs, it is necessary to apply modern methods of modeling and reducing ICE noise [4, 5] and propeller noise as well as to take into account the effects that occur in real power plant layouts on aircraft [6], performing assessments of community noise [7–9] at various stages of aircraft designing.

The aim of this study is to analyze spectral [10], energy [11], and spatial [12] characteristics of the sound field of ICE used in small and unmanned aviation.

2. Noise sources of ICE
During the operation process the ICE generates noise, which is usually divided into aerodynamic and structural [13] noise, taking into account the mechanisms of noise generation and its propagation to the environment.

Engine noise is caused by a number of factors the most important of which are:
– Aerodynamic processes that accompany the combustion of the fuel-air mixture in the cylinders, the intake of a fresh charge and the exhaust;
– Processes of mechanical interaction between the ICE elements.

This noise is distributed in the environment through the intake and exhaust systems and through the engine case. Additional sources of ICE noise are liquid cooling system, centrifugal supercharger, and turbocharging unit (if available), as well as fuel and oil pumps.

3. Spectral characteristics of the ICE sound field
The ICE noise spectrum includes tonal and broadband components. The tonal components of the ICE noise are multiples of the flashes frequency in the cylinders.

The frequencies of cylinder \( f_c \) and engine \( f_e \) harmonics in the engine noise spectrum are determined by the ratios:

\[
f_e = \frac{kn}{30r},
\]

\[
f_c = \frac{kn}{30r}.
\]
where \( k \) is a harmonic number, \( n_e \) is engine speed (rpm), \( i \) is number of cylinders connected by a common exhaust manifold, \( \tau \) is number of strokes in the engine (2 or 4).

A typical narrowband spectrum of sound pressure levels (SPL) measured during operation of the power plant of Ptero-G0 UAV in static conditions [14, 15] is presented in figure 1 as an example. The power plant includes a single-cylinder four-stroke ICE with a low-efficiency exhaust silencer and a constant-pitch two-bladed propeller. Since the engine is single-cylinder, all cylinder harmonics are engine harmonics. On the graph numbers with the indices "e" and "p" indicate harmonics at frequencies that are multiples of the frequency of flashes in the cylinder and harmonics at frequencies that are multiples of the blades passing frequency. There is no gearbox installed and so the frequency of the 4th harmonic of engine noise and the 1st harmonic of propeller noise, the 8-th harmonic of the engine noise and the 2nd harmonic of the propeller noise coincide, etc.

\[
f_e = k f_{i} , \tag{2}
\]

A 5-cylinder harmonic is the main tone for two cylinders running on separate exhausts which is consistent with experimental data for a single-cylinder engine (figure 1). Placing the main tone at a lower frequency makes a smaller contribution to the total sound pressure level in dBA. This is important in the context of ensuring low noise levels when certifying aircraft as well as ensuring low noise of propeller-driven UAVs [17].
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Figure 2. General view of the exhaust system by the ASH-62IR engine installed on the AN-2 aircraft.

Figure 3. Narrowband spectrum of AN-2 power plant noise ($\phi=120^\circ$, $R=30$ m, $n_e=2100$ rpm [16]).

4. Energy characteristics of the ICE sound field

The dependences of the noise parameters of automobile ICEs on the engine speed and load have been repeatedly cited in literature [11]. The intensity of acoustic radiation by the two-stroke carburettor engine is proportional to the engine speed in degree of 4. For carburettor gasoline engines the dependence is obtained in degree of 5 and for diesel engines in degree of 2-3. For diesel engines with volume-wall mixture formation the sound power of structural noise is proportional to the engine speed in degree 3, the displacement of the engine in degree of 2, and the average effective pressure in degree of 0.5.

Indexes of dependence of sound power on the engine speed and the available capacity of the power plant obtained by the author in the study of the power plant noise of light propeller aircrafts and UAVs in static conditions are presented in table 1.

The energy characteristics of ICE depend significantly on the design of the engine. Indexes of dependence of sound power on the engine speed close to 4 indicate the dominant role of exhaust noise without silencers. If there are effective silencers supressing the exhaust noise structural noise becomes significant and the index increases to 6.8.
Table 1. Indexes of dependence of the sound power on the available power ($N_{ex}$) and engine speed ($n_{ey}$).

| Engine                  | $x$ | $y$ |
|-------------------------|-----|-----|
| ASH-62IR                | 0.56| 3.8 |
| ROTAX-912ULS           | 4.6 | 6.5 |
| ROTAX-582UL            | 5.4 | 6.8 |
| M-14P                   | 2.8 | 3.1 |
| Two-stroke 2-cylinder engine | –  | 4   |
| SAIITO FG-40           | –   | 4.6 |

5. Directivity of the ICE sound field

The acoustic radiation directivity of ICE is determined by the design philosophy, work process-related parameters, and power conditions characterized by engine speed and load. The normalized directional characteristics of aviation ICEs averaged over six power conditions are presented in figure 4.

For the ROTAX-912ULS directional factors were obtained for arrangements on an aircraft without a bonnet (MAI-890U) and when the engine is enclosed in a bonnet (MAI-223M).

The maximum radiation directivity characteristics of the ASH-62IR and ROTAX-912ULS correspond to azimuthal angles of 0° in the front hemisphere and 135-150° in the rear hemisphere. The maximum in the rear hemisphere is due to ICE exhaust noise and the maximum in the front hemisphere is due to structural noise propagating through the engine case.

The maximum noise levels of the ROTAX-582UL correspond to the direction of 30° in the front hemisphere and 150° in the rear hemisphere.

Acoustic radiation from the M-14P occurs relatively evenly across the space in the direction of 60-120°. Minimum noise levels are observed along the crankshaft axis. A significant difference in the directional characteristics of the 9-cylinder air-cooled engines ASH-62IR and M-14P is due to:

– Differences in the way the exhaust is organized;
– The M-14P having additional controlled shutters (in addition to the bonnet) installed to improve the cooling of the engine cylinders in-flight. At the same time, shutters can affect energy and spatial characteristics of structural noise.

Directional characteristics of separate harmonic noise components as well as the total tonal radiation of a single-cylinder four-stroke ICE are presented in figure 5. The numbers of the tonal components correspond to the data in figure 1. It can be seen that the main tone that determines the intensity of the

Figure 4. Normalized directional characteristics of the overall tonal radiation by the M-14P, ASH-62IR, ROTAX-582UL, ROTAX-912ULS (with and without a bonnet) aircraft engines.
total radiation is the fifth harmonic of the engine noise which forms the direction of the total engine noise in the range of azimuthal angles of 60-135°. The complex spatial structure of the emission of separate harmonics of ICE noise may indicate that different sources dominate on different harmonics.

6. Influence of flight conditions on the intensity and direction of ICE noise
Directional characteristics of the total acoustic radiation of the engine obtained under static conditions with incident flow during tests in AK-2 anechoic chamber (TsAGI) [15] are presented in figure 6. Maximum noise levels are observed in the direction of the engine exhaust (110-120°) in the rear hemisphere.

Engine noise levels are 1-4 dB lower under the incident flow (in-flight condition) than under static conditions, depending on the direction. Despite the equality of the engine speeds the engine operates according to different, partially speed abilities. Under the incident flow the engine is less loaded which leads to a decrease in sound intensity and a change in directional characteristics.

7. Influence of load on engine noise
The influence of load on engine noise is considered in figure 7, where a comparison of 1/3-octave spectrum of sound pressure levels obtained during tests of ICE with propellers of different diameters
(0.486 and 0.508 m) under static conditions is presented. Extending the load by increasing the propeller diameter leads to an increase in the levels of the first and second harmonics of engine noise in the 1/3-octave band frequencies 40 and 80 Hz by 2 and 6 dB, respectively. At the same time, the increase in the level of the first tone of the propeller noise in the 1/3-octave band frequency of 160 Hz is only about 1 dB.

![Figure 7](image_url)

**Figure 7.** Influence of load on the 1/3-octave spectrum of sound pressure levels of the ICE (static conditions, $n_e=4900$ rpm, $\phi=120^\circ$, $R=2$ m).

Load effect on the direction of the first two harmonics of the engine noise is presented in figure 8. A significant impact of load on the direction of the second harmonic of the engine noise is obvious. It should be noted that the first two harmonics do not determine the direction of the total tonal radiation of the engine.

![Figure 8](image_url)

**Figure 8.** The influence of the load on the radiation directivity characteristic of the first two harmonics of the ICE noise (in the graph "1e" and "2e") for sound levels in the 1/3-octave band frequencies of 40 and 80 Hz, respectively (static conditions, $n_e=4900$ rpm, $\phi=120^\circ$, $R=2$ m).

The obtained results indicate that there is a link between the power conditions and the acoustic characteristics of ICE at a given power condition of the power plant.

8. **Application of an empirical model for assessing the noise of a single-cylinder gasoline engine**

Comparison of the total sound power levels calculated by the empirical model [4] of the tonal components of the ICE noise and experimental data is shown in figure 9. For all the considered engine power conditions the deviation of the calculated and experimental data does not exceed 1 dB. A similar accuracy was obtained when calculating the directional characteristics of engine noise (figure 10).
9. Methods of reducing the ICE noise
The main method of reducing the ICE noise of the intake and exhaust systems is to install silencers [18, 19]. In order to reduce the intensity of structural noise of the ICE sound-proofing bonnets should be installed [20, 21].

Installing the bonnet is an effective method of reducing noise only for ICEs with exhaust silencers. It should be noted that when installing the bonnet on the engine it is necessary to ensure its vibroisolation to avoid increased vibrations which can be an additional source of noise [15].

Based on the analysis of the certification tests database of the European Aviation Safety Agency (EASA) [22] where the results for engines with and without silencers are presented, it can be concluded that the efficiency of exhaust silencers for ICEs varies widely from 2 to 10 dBA. Often in operation standard silencers are replaced with more effective ones over time [23]. In particular [24, 25], a new silencer was developed for a single-cylinder low-power ICE with an efficiency of 5 dB higher than that of the standard exhaust silencer.

It should be noted that for modern light propeller aircraft certified according to the Chapter 10 of the ICAO standard the design condition for selecting the optimal noise silencer is take-off mode. For UAVs it is necessary to ensure maximum efficiency in cruise flight.

10. Conclusion
Spectral, energy, and spatial characteristics of the sound field of ICEs installed on light propeller aircraft and UAVs are presented. The influence of load and flight conditions on the acoustic characteristics of
the ICE is considered. The results of the calculated noise assessment of a single-cylinder ICE performed according to the author's method are presented.

Further work will focus on developing a procedure for selecting the power plant for light propeller aircrafts and UAVs taking into account the requirements for community noise. Semi-empirical methods for calculating the propellers noise and ICEs noise should become an integral part of this procedure.

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