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ECO-DESIGN STUDY OF A TURBOFAN ENGINE PRODUCT. IMPROVEMENT SOLUTIONS

Abstract: *This paper aims to analyse turbofan engines from an eco-design point of view, so that this study can highlight their future in a world based on design with as little impact on the environment as possible, as well as on people. In order to achieve this objective, we will analyse both their evolution, their impact throughout the product life cycle and improvement solutions both achieved in the past and potential solutions that can be implemented in the future.*

Key words: *Turbofan engine, emissions, pollution, noise pollution. eco-design, sustainability.*

1. INTRODUCTION

The "turbofan" engines are currently the main propulsion system of modern aircraft, mainly used in civil aviation, but also the main source of fuel in the aviation industry. It is based on a turbojet engine, to which is added the fan part in the intake area, so that the airflow is divided into two separate streams, main and secondary (Figure 1).

The main flow is the air entering the combustion chamber, while the secondary flow surrounds the engine itself, giving a higher efficiency than the turbojet engine in subsonic flight [1].

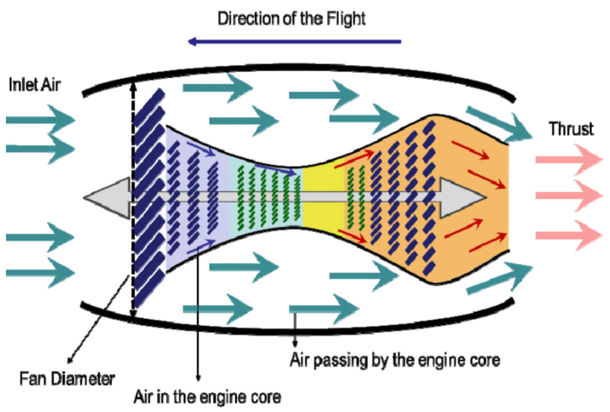

Figure 1 Air flows in a turbofan engine [2].

The first designs of these began in the interwar period, some models were even tested on the test bench during the Second World War, but due to the war and the lack of materials, the project was not continued. Thus in the 1950s the first mass-produced "turbofan" engine appeared, produced by Rolls-Royce, and used on various types of aircraft, notably the Boeing 707. With it, their evolution has seen considerable progress, both in terms of efficiency and in terms of pollution, both generated by emissions and noise pollution and pollution generated by its manufacturing processes.

Today, the aviation industry has seen an exponential increase in the number of daily flights, so engine design requires increased environmental attention throughout its life cycle.

2. PRESENTATION OF TURBOFAN ENGINES

2.1 Classification of turbofan engines

The classification of turbofan engines can be made according to various characteristics, the most relevant characteristic being the bypass ratio. This is the ratio of the total flow mass flow to the main flow mass flow.

Thus a first classification is according to this ratio, with low BPR engines, up to 2:1, examples being the first types of turbofan engines, as well as the current engines used by fighter aircraft, while high BPR engines are represented by most modern aircraft, currently reaching values of up to 12.5:1 in the case of the Pratt&Whitney PW1000G engine found on the A320neo. As this ratio increases, an average ratio of between 2:1 and 5:1 can be defined, found for example on private jet aircraft [3]. Another method of classification is determined by the exhaust stream, which can have both streams mixed or separated.

A third method is based on the construction principle, so the engine can have a single connecting shaft between compressor, turbine and fan, two shafts or three.

2.2 Operating principles of turbofan engines

The turbofan engine achieves thrust through Newton's third law of motion, applied to aerodynamics, whereby "when one body acts on another body with a force (the action force), the second body acts on the first body with a force (the reaction force) of the same size and direction, but in the opposite direction".

These engines, also known as a double-flow turbojet engine, are designed on the basis of a small single-flow turbojet engine, with a turbine-driven fan in front of it, surrounded by an air circulation zone, which is introduced and compressed by the fan. Thus, the airflow is divided into two separate streams, a primary one entering the turbine to mechanically drive the fan and other components, and a secondary one representing 70-80% of the thrust force, surrounding the turbine, thus having a good efficiency at subsonic speeds and a low specific consumption compared to other engine variants.

2.3 Main components of a turbofan engine

The main components of a turbofan engine are: fan, compressor, combustion chamber, turbine, exhaust nozzle, shaft, engine casing (Figure 2).

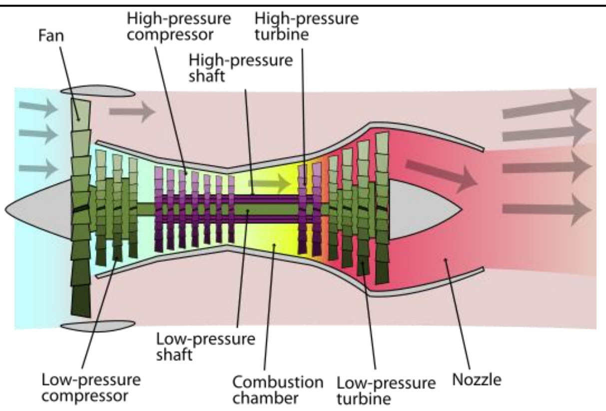

Figure 2 Main components of the turbofan engine [4].

The main improvements in efficiency offered by this type of engines are due to the evolution of the materials used, as well as the design and manufacturing techniques, as follows:

Fan: this ensures air intake into the engine behaviour and is the main factor for increasing efficiency. This increase is proportional to its diameter, so increasing its size results in higher efficiency. To achieve this, both lightweight and strong materials are needed to withstand centrifugal force.

Compressor: this compresses the air to ensure sufficient airflow for combustion. In general, it is currently made up of two groups, the high-pressure compressor and the low-pressure compressor, the axial compressor type.

Combustion chamber: compressed air is mixed with fuel and this mixture is ignited when the engine is started by spark plugs, maintaining combustion throughout the engine's operating cycle. Its efficiency is the main factor influencing particulate and greenhouse gas emissions.

Turbine: the main component that ensures the operation of the engine and other aircraft components. It is subject to both high mechanical forces and high temperatures of around 1500°C.

Exhaust aid: it has the role of transforming the internal energy of the resulting gas into propulsive force, through the Venturi effect.

Shaft: this transfers the rotational motion of the turbine to the compressor and fan.

3. DESIGN PRINCIPLES IN TERMS OF ECO-DESIGN

Eco-design design is found throughout the entire life cycle of the product, from the establishment of the necessary parameters to its disposal. This takes into account both the limitation of pollution due to the combustion operating regime, resulting in emissions of greenhouse gases or harmful to the environment and human health, and noise pollution and pollution generated by the processes necessary for its manufacture, transport and disposal.

Thus, design itself has played the main role in the development of turbofan engines, both through the evolution of the materials and technologies used and through the development of computerised testing methods. The first engines used in series production had a theoretical thermodynamic efficiency of 39%, but in reality this was around 28%. Today, an example of this is the General Electric GE9X engine found on the Boeing 777 aircraft, which has an efficiency of 50-55%. This efficiency is based on its development using composite materials, high-pressure compressor units as well as cooled blade turbines to withstand a high turbine face temperature duty cycle. Thus, with these materials and design methods, it has been possible to increase the BPR ratio and achieve higher efficiencies. It is currently assumed that a maximum efficiency of 60% can be achieved.

The next step after engine design is engine manufacturing. This is a complex, time-consuming and energy-intensive process. This energy consumption is represented both by the manufacture of components and the necessary materials, such as carbon fibre, and by the transportation of components from different suppliers to the assembly site.

The product's operating period is the most costly stage in its life cycle, with both noise and emission pollution. It also includes maintenance, which is necessary both for the proper functioning and sustainability of the product.

The last stage in its life cycle is represented by its decommissioning, which is a process that needs to be analysed from the design phase, so that some of the components found in its assembly can be reused or recycled.

In this whole life cycle, the most important aspect is the financial factor, so its development is limited. So its realisation will always be a compromise between cost, emissions, noise and consumption.

This can be seen in Figure 3, where a Pareto diagram is shown, representing the four design options according to the requirement.

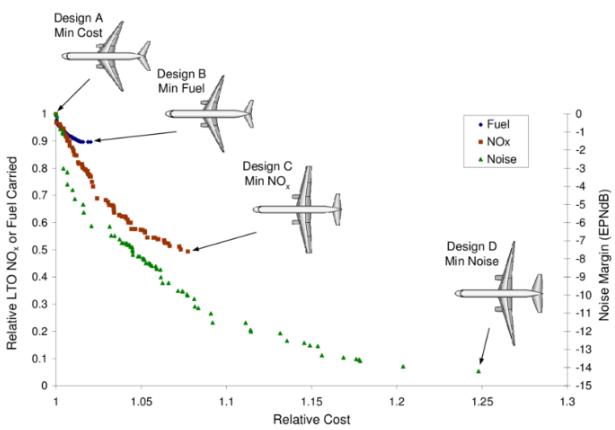

Figure 3 Pareto diagram of aircraft design [5].

Thus, it can be approximated that for a 15 decibel decrease in noise and a 50% reduction in emissions, operating costs will increase by 10-25%, while the reduction of nitrogen oxide pollutant emissions in the take-off-landing cycle will require higher fuel burn and higher noise, as the reduction in emissions is due to higher engine speed.

4. ANALYSIS OF THE MAIN POLLUTION FACTORS OF TURBOFAN ENGINES

4.1 Pollution due to emissions

Pollution due to emissions is the main concern for mankind in the 21st century', as an upward trend in average annual temperatures can be observed since the beginning of the industrial era, which is correlated with greenhouse gases such as carbon dioxide and nitrogen oxides. At the same time, other emissions such as carbon monoxide, sulphur oxides and black carbon particles can affect human health locally, as well as climate change such as acid rain. Figure 4 shows the chemical process of fuel combustion in turbofan engines, and the main combustion products.

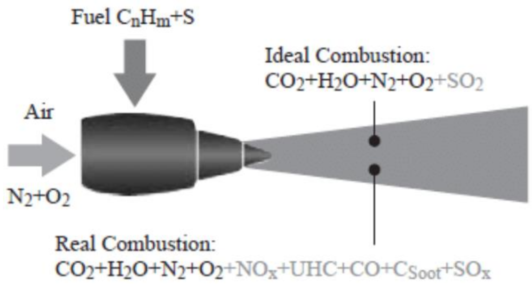

Figure 2 Fuel combustion process in turbofan engines [6].

Thus, in Table 1, the emission quantities in 2006 for the aviation industry are presented, anticipating a multiplication factor of 3-4 by 2050 due to the increasing demand for flights.

Table 1

Quantity of emissions in 2006 resulting from the operation of turbofan engines

Type of emissions	Amount of emissions (Tg= 1.000.000 m^3)
Carbon dioxide emissions	162.5
Water vapour emissions	232.8
Nitrogen oxides emissions	2.656
Carbon monoxide emissions	0.679
Sulphur oxides emissions	0.111
Hydrocarbon emissions	0.098
Emissions of organic particles	0.0030
Sulphuric particle emissions	0.0023
Emissions of black carbon particles	0.0068

Carbon dioxide is one of the main compounds resulting from the combustion of kerosene, with 3.15 kg of carbon dioxide emitted for every kilogram of kerosene used. It does not have a direct toxic or polluting effect, but it is the main factor causing the greenhouse effect, and this is accentuated by its lifetime in the atmosphere, with a half-life of 30 years.

In order to be able to analyse the effects of the aviation industry compared to other means of transport, it is necessary to define a relationship between the amount of fuel used in relation to the number of passengers and the number of kilometres travelled.

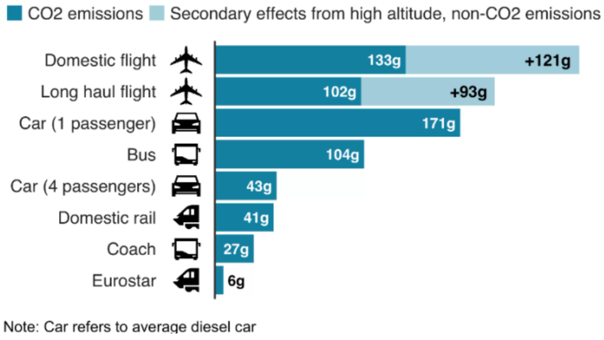

Figure 3 Graph of carbon dioxide emissions for different means of transport [7].

Thus, according to Figure 5, the transport efficiency of the aviation industry is similar to that of bus transport, which is accentuated by the emission of carbon dioxide at high altitudes.

In recent years, the airline industry has made considerable progress in this respect, both through technological development and by making routes more efficient and filling a significant percentage of aircraft capacity. An example of this is the Boeing 737, which is also one of the most frequently used aircraft in the industry. The first model, the Boeing 737-300, built in 1984 had an efficiency of 3.46L/km/seat, while the 737 MAX aircraft built in 2017 had an efficiency of 2.28L/km/seat.

Emissions of water vapour, nitrogen oxides, sulphur oxides and soot have a particularly local effect in the vicinity of airports.

Nitrogen oxides are represented by nitrogen monoxide, nitrous oxide and nitrogen dioxide, which have different properties and effects. Nitrogen monoxide is a colourless, odourless gas, which in high concentrations above 150 ppm can become toxic. Nitrogen dioxide is a reddish-brown, chlorine-smelling, droughty and toxic gas, which can cause acid rain, affecting the environment and leading to building damage. Nitrous oxide is colourless, non-toxic but it contributes to the greenhouse effect, having an effect three hundred times stronger than carbon dioxide, and a lifetime of over 100 years in the atmosphere. It also affects the ozone layer in the atmosphere. They occur at engine power speeds, and are 30-50 times higher at take-off than at idle. Despite technological developments, it is not possible to eliminate them from the combustion process, while limiting them by using a combustion chamber with an initial combustion using a rich fuel mixture, with air being added later in the process, thus increasing operating costs.

Another compound that results from the actual combustion of kerosene in the turbofan engine is carbon monoxide. It is produced in a similar way to unburned hydrocarbons at low engine speeds, being 10 times higher at idle than at take-off at 85% engine power. Carbon monoxide is a colourless and odourless gas that causes haemoglobin damage, which in high concentrations, 0.16% by volume of air, becomes lethal.

The evolution of carbon monoxide reduction can be seen in the Figure 6, it is considerably reduced.

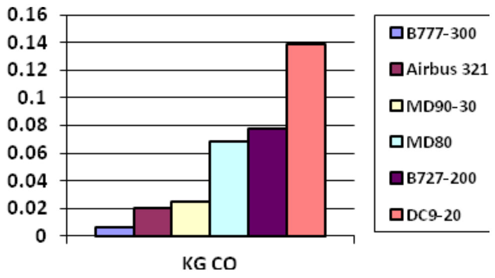

Figure 6 Carbon monoxide emissions per passenger per hour ($kgCO_2$/passenger/hour).

Unburned hydrocarbons are another element resulting from the actual combustion, especially in the case of turbofan engine operation at low power, such as in the case of taxiing on the airport apron (Figure 7). Thus they are a problem in particular for airport staff as well as for nearby residential areas.

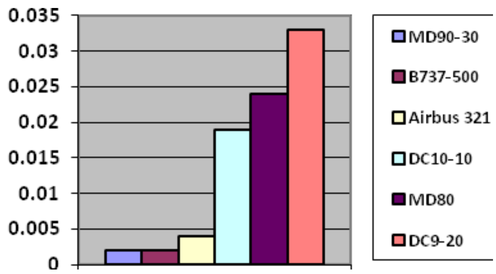

Figure 4 Unburned hydrocarbons (kgHC/passenger/hour).

As with carbon monoxide, these have been drastically reduced over the last 50 years, but due to the much higher frequency of flights, they still pose a potential hazard. Thus, although the technological development of turbofan engines has led to a decrease in the emissions generated, the frequency of flights has increased during this period, as can be seen in Figure 8.

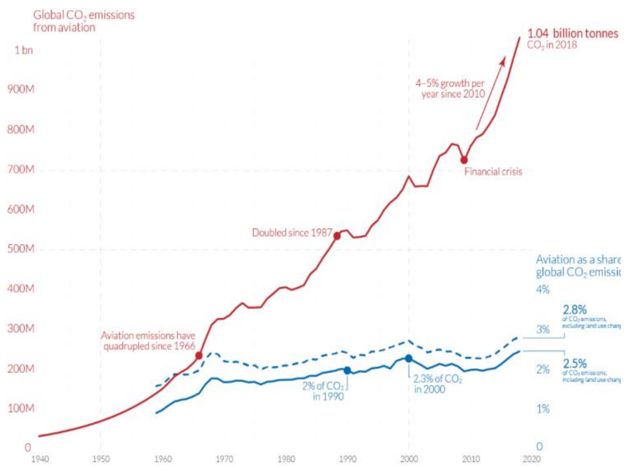

Figure 5 Carbon emissions from the aviation industry 1940-2020 [8].

It can be seen that in 1987 carbon dioxide emissions doubled compared to 1966, and today they are about 5 times higher than in 1966, with an increase of at least 4% each year, resulting in ever-increasing pollution, despite the fact that the engines have almost reached their theoretical maximum efficiency, so that design solutions in future development consist of modifying the operating principle, such as:

- Hybrid turbofan engines: addition of an electric motor to support the conventional engine during take-off and landing cycles, where efficiency is low, thus helping to both save fuel, lower pollutant emissions and reduce noise pollution during ground manoeuvres.
- Alternative fuels: biojet and hydrogen are the main potential alternatives to conventional fuel. Biojet is produced from renewable raw materials such as vegetable oils, animal fats and algae, with the benefits of reduced emissions and renewable sources. Hydrogen, on the other hand, emits no carbon when burned, so carbon emissions are excluded. In the short term, it can also be mixed with conventional fuel so that the impact on the engine is minimal, offering a transition to greener technologies.

4.2 Noise pollution

One of the most direct effects of air traffic is noise pollution, especially around airports. This problem has been reported since the early days of civil aviation, when both turbojet and piston engines were prevalent.

With the increase in air traffic, noise pollution has increasingly affected residential areas adjacent to airports as well as those where landing and take-off strips are located. In addition, aircraft noise has been a factor in reducing flying conditions for both passengers and pilots. The main negative effects attributed to noise pollution are categorised as follows:

- Social effects: migration of population from airport areas;
- Biological effects: direct, such as hearing impairment, and indirect, such as psychological effects;
- Material effects: premature wear of various installations.

Biological effects are found among passengers, aircraft crew and residents in the airport area, and can have various harmful effects among them, as illustrated in Figure 9.

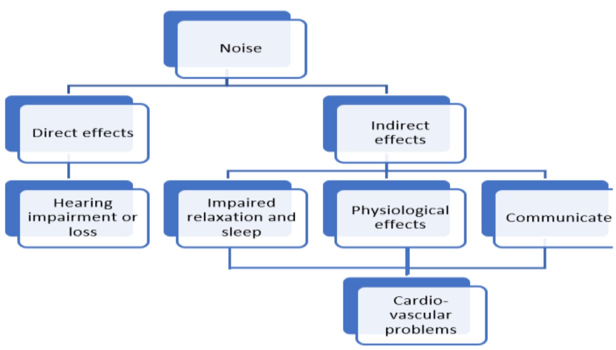

Figure 6 Health effects of noise pollution.

Since 1976, ICAO has imposed a series of noise pollution measures, setting a reference value of 86-106 decibels, depending on the flight stage, the number of engines and the aircraft weight, called stage three, the second and first being assigned to aircraft older than this period. In 2006 the fourth stage won, with values 10 decibels lower than the third stage, while in 2017 the fifth stage came with a standard 7 decibels lower than the previous one. This cataloguing is shown below in Figure 10.

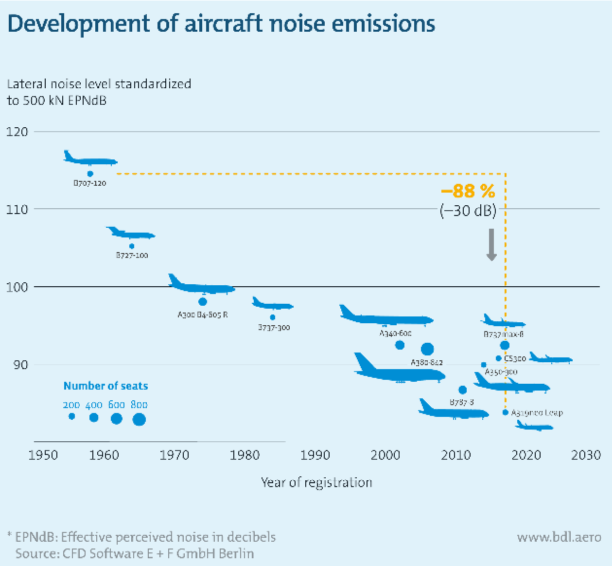

Figure 10 Evolution of noise emission.

Thus, these representations of noise pollution can also be represented as in Figure 11**,** thus making it possible to geographically highlight the importance of these regulations as well as the area in which the population may be affected by the operation of airports.

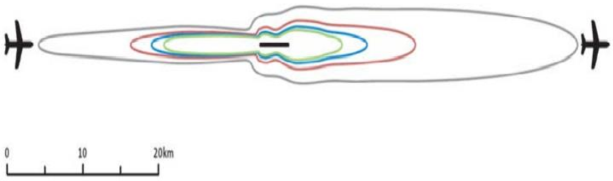

Figure 7 Area affected by noise pollution.

A good example of this is Henri Coanda airport in Otopeni and Aurel Vlaicu airport in Bucharest. In the case of both airports, the residential area has developed around them, so that, at present, noise pollution is a major factor both harmful to the population and an economic factor, resulting even in the closure of Aurel Vlaicu airport for commercial flights.

Figure 12 shows the noise map of Henri Coanda airport, being mainly affected the area of Otopeni, Buftea, Dimieni Tunari, and partially Mogosoaia.

Thus, for the city of Otopeni a value from 45 decibels to over 75 decibels can be observed. Thus its operation is limited at night, with minimal take-offs and only landings.

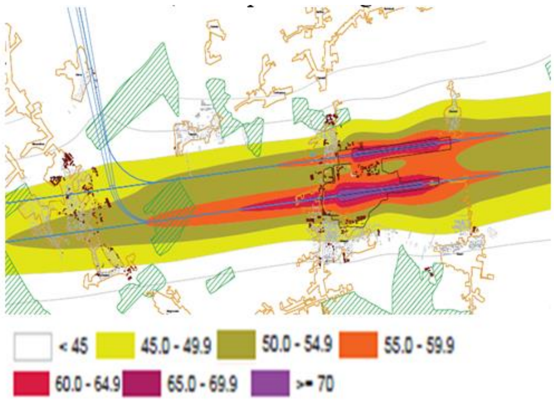

Figure 8 Henri Coanda International Airport Noise Map [9].

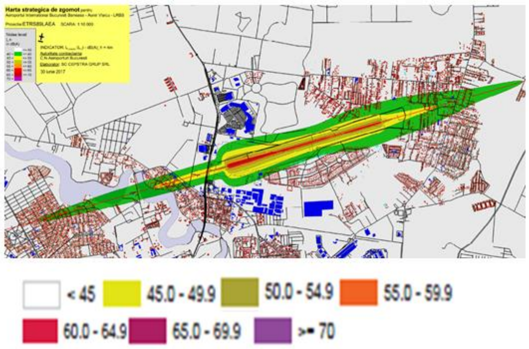

Figure 9 Baneasa-Aurel Vlaicu airport noise map [9].

In the case of Aurel Vlaicu airport, noise pollution affects a significant percentage of the population located in the north of Bucharest, figure 13, so following public pressure it was closed in the period 2014-2023.

Currently, commercial flights have resumed on it, with the noise pollution regulation only doubling the cost of night-time operations as a deterrent.

From the point of view of turbofan engines, it is possible to observe the drastic decrease in noise pollution through their development in recent years, so that the decrease in noise generated by them will lead to a significant increase in development costs. However, a series of measures can be imposed, such as the development of engines with a view to potential improvements, so that older generation engines have a lower noise compared to the time of its development.

Other measures that can be imposed concern both local government and the management of airports and aviation authorities and even manufacturers and airlines in this way:

- From a local government point of view, noise measuring devices can be implemented at various distances from the airport, as well as the implementation of forest barriers and green spaces. At the same time, the local administration should limit and regulate the development of residential areas around airports.
- From the airports' point of view, they can implement noise barriers around airports, such as absorbent panels or earth barriers, as well as increasing operating costs depending on the time of day and the number of affected population.

- Aviation authorities can impose both restrictions on older generation aircraft and restrictions around certain airports in densely populated areas.

Both solutions such as absorbing panels and noise barriers, Figure 14, can mean for many residential areas a significant decrease in noise, so that the noise produced by the engines during take-off is limited during the runway run, thus achieving a noise exposure time at least halved.

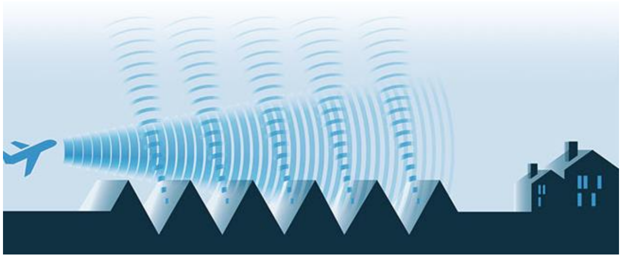

Figure 10 Noise dispersion effect of the sound barrier [10].

5. CONCLUSIONS

Thanks to technological development, turbofan engines have almost reached a maximum degree of efficiency, both in terms of operating parameters and in terms of the pollution generated, modern aircraft have a consumption of less than half compared to older generation aircraft [11]. At the same time, the industry has grown significantly, especially in recent years, so that the actual pollution generated has increased significantly, both in terms of emissions and noise pollution.

Thus, as a conclusion from this study, the improvements that can be made to turbofan engines using conventional fuel are limited both technologically and especially economically, and they bring small improvements compared to the cost required. The main improvements that can be made in terms of emissions are the adoption of alternative fuels, electric assist for turbofan engines, as well as more efficient ground idling and running times. Another set of measures to tackle emissions pollution are related to the development of airports and their operation, so that for relatively short distances, other means of transport are preferred, such as rail transport on electrified lines, air transport being efficient for longer distances.

From the point of view of noise pollution, improvements can come both from hybrid electric engine operation, but much more significantly from a series of administrative measures, such as the installation of sound-absorbing panels, noise barriers, adaptation of flight routes and times so as to avoid populated areas, and legislation, so that the proximity of residential areas to airports is as limited as possible.

As a final conclusion, although turbofan engines have reached an upper limit in terms of efficiency, there are both direct and indirect solutions to ensure a more efficient future for the aviation industry, with minimal environmental and population impacts, both in the short and long term.

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