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Sonic Boom Mitigation Through Shock Wave Dispersion

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Abstract

Lately, the interest for passenger space planes, supersonic passenger aircraft, and supersonic business jets has greatly increased. In order to mitigate the sonic boom effects at ground level, some aerospace companies proposed airplanes that have a very small transversal fuselage section or that have a curved ("shaped") fuselage. Obviously, shaping the fuselage leads to the increase of dynamic drag and manufacturing cost. Reducing the fuselage transverse section leads to reducing the useful volume inside fuselage and increases the landing distance of aircraft. The solution presented in this chapter shows that it is theoretically and technologically possible as the shock wave to be dispersed through mechanical or electrical means. The shock wave is in fact a stationary effect generated by the move of aircraft with constant speed relatively to surrounding air. If this feature is in a way or another canceled, the shock wave is dispersing. Due to dispersion of the shock wave the 'N' wave at the ground is tens of times larger and the sonic boom is correspondingly lower. The shock wave dispersion system of the future could be mechanical or electrical is activated only when the supersonic aircraft/space plane is flying horizontally over community.

Keywords: sonic boom mitigation, shock wave dispersion, supersonic aircraft, supersonic business jet, space plane

1. Introduction

The first manned airplane, which exceeded the speed of sound in horizontal flight was the American airplane X-1 manufactured by Bell Aircraft Corporation [1]. On the 14th of October 1947, the X-1 aircraft was air-launched at the altitude of 7000 m from the bomb bay of a Boeing B-29 and then climbed to the test altitude of 13,000 m. Piloted by Chuck Yeager, the aircraft reached a speed of 1127 km/h (Mach = 1.06) in horizontal flight. Since the maiden flight, the aircraft accumulated a number of 78 flights and on the 26th of March, 1948 it attained a speed of 1540 km/h (Mach = 1.45) at the altitude of 21,900 m.

Because at that time no jet engine was powerful enough, the aircraft Bell X-1 was powered by a four-chamber XLR-11 rocket engine that produced a static thrust of 26.5 kN. This was the first time when the sonic boom was revealed as a natural phenomenon generated by the aircraft breaking the sound barrier. In essence, the sonic boom is the manifestation of the shock waves generated by a supersonic aircraft perceived at ground level.

After this important event, a multitude of supersonic aircraft having exclusive military applications was developed and manufactured in series by the most technologically advanced countries. Simultaneously, the phenomenon of sonic boom was intensively researched from a theoretical and experimental point of view [2–6].

At the beginning, due to the fact that the interest for the supersonic flights was exclusively for military applications, the ecological impact of sonic boom was not taken into account.

However, on the 2nd of March 1969, the first flight of Concorde supersonic passenger aircraft took place. This aircraft was produced by the French company Aerospatiale and British Aircraft Corporation (BAC). Concorde was a large enough aircraft (much larger than a usual military supersonic aircraft) to reveal the extremely high negative environmental impact of the sonic boom [7]:

Length: 62.19 m
Wingspan: 25.6 m
Height: 12.19 m
Empty weight: 79,260 kg
Capacity: max. 144 passengers
Maximum speed: Mach 2.04 ($\approx$2179 km/h) at cruise altitude
Cruise speed: Mach 2.02 ($\approx$2158 km/h) at cruise altitude
Range: 7222.8 km
Service ceiling: 18,290 m

On the 24th of October 2003, Concorde operated its last flight, leaving the aircraft market and airspace. An important reason was the impact of the sonic boom produced on the environment/community.

This fact raised the interest for sonic boom mitigation. Thus, important papers [8–11] were written on this subject, and a number of solutions for sonic boom mitigation were filled in patent [12–18].

Lately, an important change on the aircraft market took place: the start of a high demand for supersonic business jet and a continuous rise of interest for very high-speed passenger transportation, supersonic and hypersonic airliners.

An important problem generated by supersonic aircraft is the effect of sonic boom at the ground level. The sonic boom is an "N"-shaped pressure distribution, which spans the ground when an aircraft is flying at supersonic speed. The lower the flying height, the higher the material damages and annoyance produced in community.

This problem blocked the development of supersonic civil aircraft for a long period of time.

The state of the art regarding the solutions for mitigation of sonic boom effects at ground level is presented in Chapter 2 together with the drawbacks of these solutions.

In the next points of this chapter, the authors underline some important characteristics of shock wave, which support a new possible solution to mitigate the sonic boom impact at ground level: dispersion of shock wave mainly through vibration of aircraft nose surface and wing leading to edge surface. The explanation is simple: the shock wave is a steady-state effect, which is generated through moving of aircraft with a constant speed. If this steady-state characteristic of flight is canceled through vibration of the specified surfaces, the shock wave is dispersed, and its effect at ground level (known as "sonic boom") is greatly reduced.

2. The state of the art

For reducing sonic boom effects at ground level, companies as Supersonic Aerospace International, Lockheed, in collaboration with NASA, Boeing, Airbus,

Dassault, and Aerion Corporation proposed airplanes having thin or curved (shaped) fuselages, and other designers proposed biplane type aircraft.

Some design solutions are presented in **Figures 1** and **2** [19]. The long aircraft having a small cross section (**Figure 1**) needs a too long landing distance, and the space for passengers inside fuselage is small. Nevertheless, it seems that this solution began to be preferred at present by aircraft manufacturers. This preference is explained by the manufacturing costs that are low because no major change in the current technology is necessary.

Obviously, the curved (shaped) fuselage (**Figure 2**) strongly perturbs the airstream flowing around the aircraft. As a result, more power is required for flight. At the same time, the curved fuselage considerably increases the manufacturing costs of aircraft.
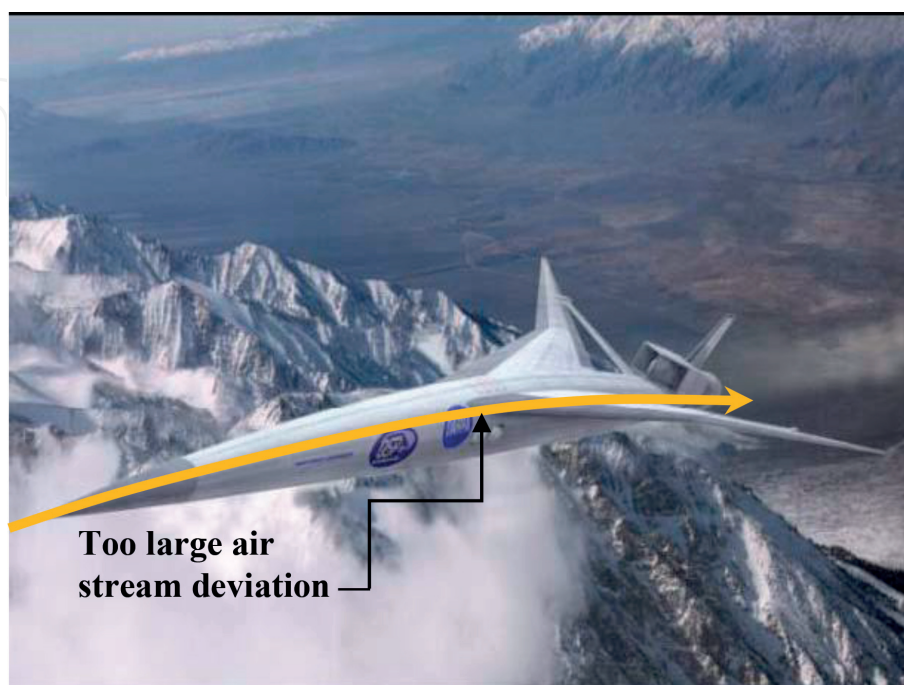
Figure 1.
An advanced Lockheed Martin concept [19].

Figure 2.
An advanced Northrop Grumman concept [19].

For a very long period of time, the "shaping" solution was the preferred one. According to this solution, shaping the fuselage leads to the changing of the "N" wave shape at ground level and mitigation of its impact.

The theory of sonic boom mitigation through shaping was established during the 1960s–1970s with the papers written by Seebass, Carlson, and Darden [8, 20, 21]. This theory was not proven until 2002.

In 2002, the Defense Advanced Research Projects Agency (DARPA) selected several companies for the Phase II of the Quiet Supersonic Platform (QSP) program [22]. The allocated research funds were of about 9 million USD. The selected companies were the following:

• Lockheed Martin, Advanced Development Company, Palmdale, California

• Northrop Grumman Corporation, El Segundo, California

• Arizona State University, Tempe, Arizona

• General Electric, Cincinnati, Ohio

These system integrators updated their aircraft and engine designs and technologies; performed validation of their designs, utility, and cost analysis; and developed technology maturation roadmaps.

Additional funds were received by Northrop Grumman Corporation to conduct flight demonstration of direct sonic boom mitigation using a modified F-5E aircraft.

A special nose glove was designed for modification of aircraft to produce a shaped sonic boom profile with a lower impact at the ground level. Before the flight demonstration, tests done in wind tunnel validated the computed sonic boom signature predictions for the modified F-5E aircraft. A series of flight tests validated the predicted persistence of shaped sonic booms.

This program was very important because it demonstrated for the first time that an appropriately shaped aircraft can mitigate of sonic boom.

The experimental F-5E aircraft modified by Northrop Grumman Corporation (named F-5 Shaped Sonic Boom Demonstrator (SSBD)) is presented in **Figure 3** [23].

The theory was proven to work under practical design, fabrication, flight, and atmospheric conditions. Results of tests confirmed that shaping was successful in altering the sonic boom signature at the ground. Ground measurements matched predictions (flattop modified waveform relative to N-wave unmodified vehicle, **Figure 4**) [23]. In **Figure 4**, one can see that the "N" wave is no longer sharp in the case of shaped nose of F-5 SSBD (blue line) in comparison with the case of unmodified aircraft F-5E (red line). During this experiment, sonic boom reduction technology worked by achieving a shaped sonic boom, validating that shocks could be kept from coalescence all the way to the ground.

The image of modified aircraft from **Figure 3** shows at a glance the important drawbacks of this solution, affecting aerodynamic characteristics, frame's strength, weight, useful volume, and manufacturing cost of aircraft. An acceptable compromise is difficult to be found especially in the case of large passenger aircraft.

These drawbacks of shaping solution oriented the aircraft manufacturers to solution of supersonic aircraft with very thin fuselages. The first supersonic business jet is expected as to be Aerion AS2 which will be launched on market in 2023 (**Figure 5**) [24].

Main characteristics of this aircraft are [24]:
Supercruise: 1.4 Mach

Figure 3.
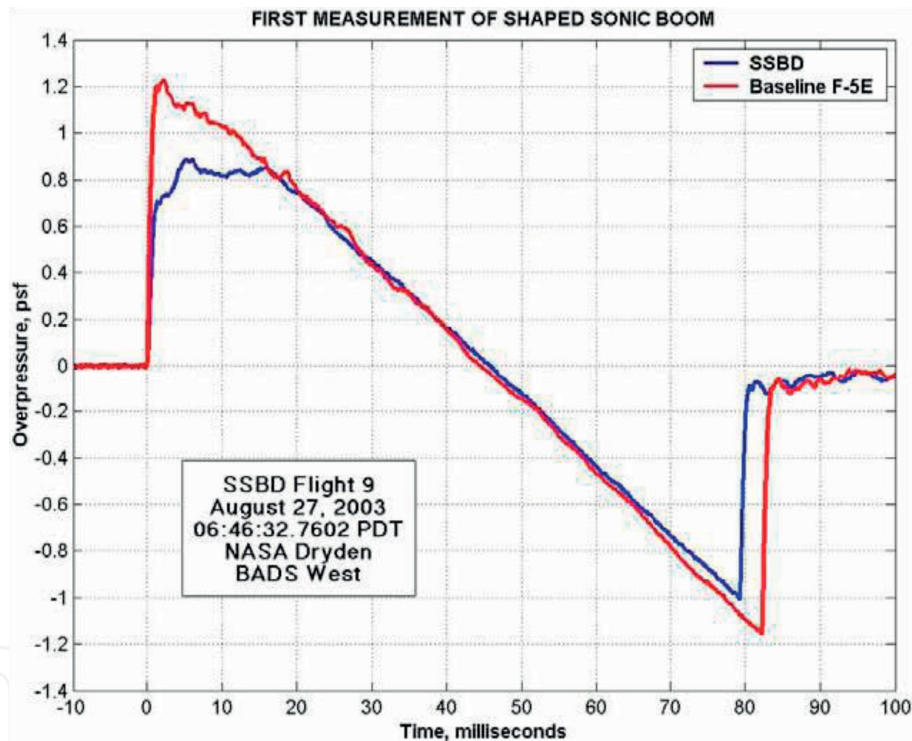*The F-5E aircraft modified by Northrop Gruman [23].*

Figure 4.
First measurement of F-5E-shaped sonic boom aircraft modified by Northrop Gruman [23].

Boomless cruise: 1.1–1.2 Mach
Long range cruise: 0.95 Mach
Max. range, Mach 1.4: 7780 km
Max. range, Mach 0.95: 10,000 km
Wing area: 140 sq.m
Interior dimensions:
Height: 1.9 m
Width: 2.2 m
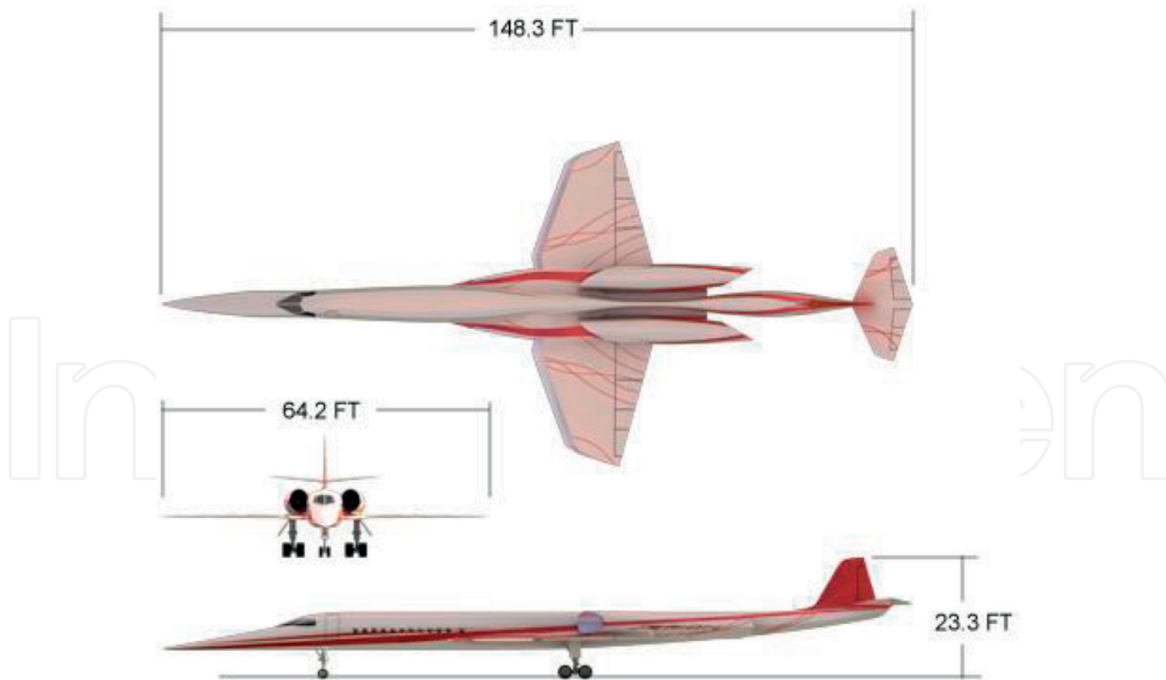Cabin length: 9.1 m
Exterior dimensions:
Length: 51.8 m

Figure 5.
Aerion supersonic business jet [24].

Wingspan: 23.5 m
Height: 6.7 m
Fuel quantity: 26,800 kg
Looking to the lengths of cabin (9.1 m) and aircraft (51.8 m), one can see at a glance one of the most important drawbacks of this solution: The space for passengers is extremely low due to the need of the aircraft fuselage to be very thin and long.

3. The theory of Sonics: A quick review

In 1918, the Romanian scientist George Constantinescu published *The Theory of Sonics* [25]. This book presents a new theory on the use of waves in the production, transport, and conversion of mechanical energy, as well as experimental validation. Constantinescu applied his theory to longitudinal waves of pressure propagating
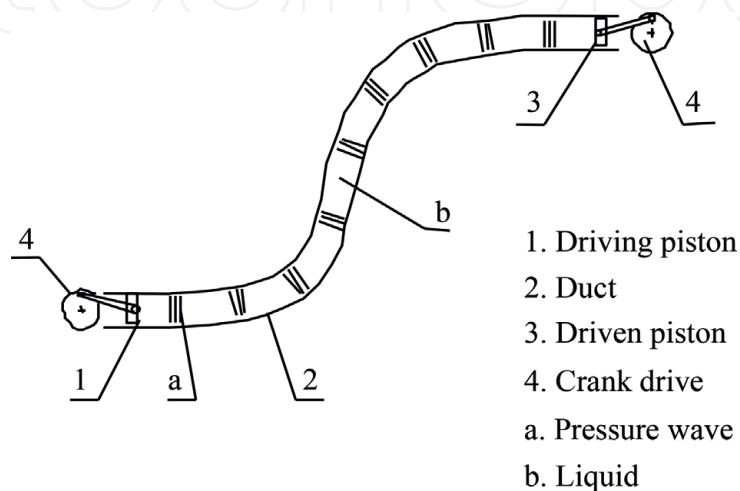

1. Driving piston
2. Duct
3. Driven piston
4. Crank drive
a. Pressure wave
b. Liquid

Figure 6.
Basic principle of the theory of Sonics [25].

through liquids, which fill metallic ducts. These ducts act as "wave guides" (see **Figure 6**). Piston, 1, oscillates in a sinusoidal manner and creates longitudinal waves of pressure, a. These waves propagate through liquid, b, which fills duct, 2, and actuates driven piston 3. Pistons 1 and 3 are going to oscillate with the same frequency. Crank drives, 4, assure the continuous motion of pistons. This method of power transmission relies on liquid compressibility. The phase difference between pistons 1 and 3 depends on the ratio of duct length and wavelength. If this ratio is an odd number, pistons 3 and 1 oscillate in opposition (i.e., the phase difference is equal to π). The amount of power that can be transmitted is proportional to the pressure of liquid within duct. Finally, George Constantinescu demonstrated that sonic waves act like alternative current and built many wave generators and sonic engines with power of tens of kW. Frequencies of sonic waves used for power transmitting can be from several tens to tens of thousands of Hz.

4. New solution for sonic boom mitigation

This new solution was proposed for the first time in a previous paper of authors [26]. It consists in dispersion of shock wave during its generation by an aircraft in supersonic flight having as a consequence extension of "N" wave (sonic boom) on a much larger area at ground level. In this way, the impact of sonic boom on community is much reduced.

This solution offers to aircraft designers the possibility to create supersonic aircraft with a larger space in fuselage and transportation of a higher number of passengers.

4.1 The bases of the new solution

The new proposed solution for sonic boom mitigation is based on the following observations:

1. The shock wave is a steady-state effect, which appears when the speed of aircraft is higher than the speed of sound in air.

2. For low values of Mach no. (M = 1, … 1.8), a low variation of the semi-angle α of a wedge, which is placed in a supersonic stream produces a larger variation of shock wave angle, β.

The thickness of shock wave is extremely small. This thickness depends by Mach number as presented in **Figure 7** [27]. For this reason, when the shock wave hits the ground, a sudden increase of local air pressure is produced.

According to Observation 1, in normal circumstances, the shock wave cannot be eliminated because it is a physical effect governed by natural laws. However, if circumstances are changed, for example, the steady-state is substituted with a transient state; the effect of sonic boom on ground surface will be much reduced.

Taking as example the oblique shock wave created by a wedge having the semi-angle α (**Figure 8**), the semi-angle β of the shock wave is given by Eq. (1) [28]. Looking to Eq. (1), one can see that β is depending on the semi-angle α and the speed of aircraft given by the Mach number, M:

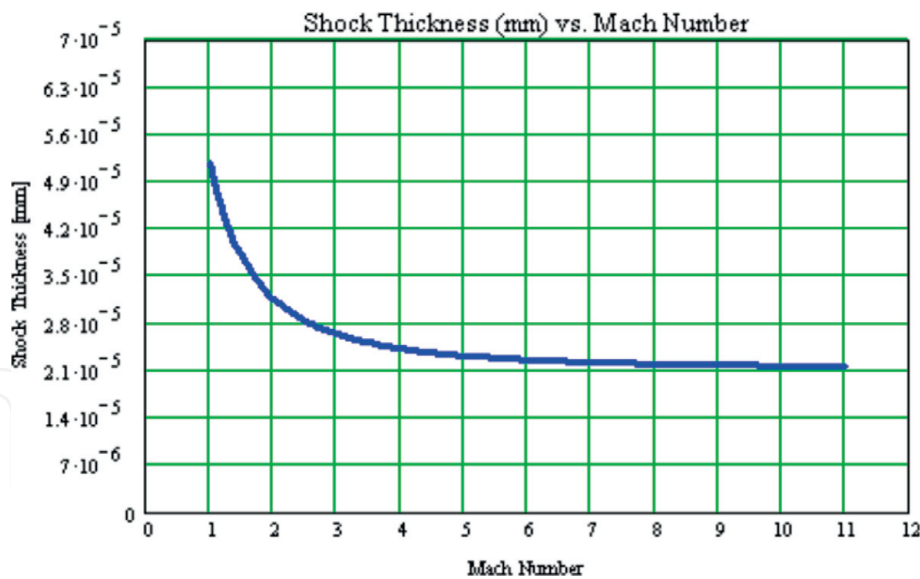$$\cot \alpha = \tan \beta \left[\frac{(k+1)M^2}{2(M^2 \sin^2 \beta - 1)} - 1 \right] \tag{1}$$

Figure 7.
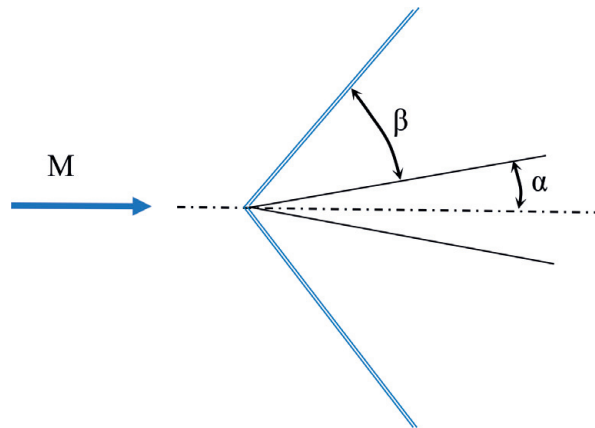*The thickness of shock wave [27].*

Figure 8.
The oblique shock wave.

A transient state could be produced in two ways:

a. Increasing and decreasing of aircraft speed (Mach number, M)

b. Increasing and decreasing rapidly the semi-angle α.

The first way (a) is impossible due to inertia. Really, it is obviously for everybody that the aircraft cannot be accelerated and decelerated rapidly because the thrust of engines cannot be increased and decreased rapidly.

The second way (b) is affordable if the supersonic aircraft is equipped with an equipment for dispersing of shock wave during flight over populated areas.

In this case the dispersion of shock wave, i.e., variation of angle β, is produced through periodical variation of semi-angle α of aircraft surfaces, which generate the shock waves, i.e., nose, wing leading edge (LE), and horizontal empennage LE.

During horizontal flying of a supersonic aircraft, its nose produces a conical shock wave, and the wing and horizontal empennage are producing oblique shock waves.

Therefore, three booms should be heard at ground level, but the second and the third booms are very close, and practically only two booms are heard.

During the travel of the three shock waves to ground, "N"-shaped wave is formed through coalescence hitting the ground as sonic boom. This "N" wave is composed by a high-pressure zone, where maximum pressure is $+P_0$ followed by a depression zone where minimum depression is $-P_0$.

4.2 Mechanical dispersion of shock wave using elastic membranes

In normal case, the shock wave thickness δ is extremely small as presented in **Figure 7**, and the footprint length d of the "N" wave at ground level is about two times larger the aircraft length.

For simplicity, assume an aircraft wing having the wing LE as a wedge, which can be continuously vibrated with a certain frequency, ν (**Figure 9**) [26].

Vibration of wing LE surface is done in this case by an elastic membrane, which is stretched over the wing LE. Between the wing and membrane, a thin layer of hydraulic liquid is introduced. When pressure pulses of a certain frequency ν are injected in liquid through perforations in wing LE, the membrane begins to vibrate with the same frequency ν. The pressure pulses can be produced by a sonic equipment as presented in **Figure 6**. In this case, the driven piston 3 from **Figure 6** is substituted by the elastic membrane.

For reaching of a high vibration amplitude, the injection frequency of pulses must coincide with the first resonance frequency of membrane. The resonance frequency of membrane depends on the value of stretching tension of that membrane over the wing LE.

In **Figure 9**, one can see that when semi-angle α increases, the shock wave semi-angle β increases, and the shock wave is dispersed on a larger area D > d. Due to dispersion, the thickness of shock wave at ground (S) is much larger than the thickness of the shock wave (δ) in the absence of vibration (S >> δ). Extension of shock wave on a larger area at ground level makes the maximum pressure $p_0 < < P_0$ and the impact of sonic boom on community to be much reduced.

According to observation 2, if the Mach number is between 1 and 1.8 (the case of the most supersonic business jet ongoing projects), a small variation of semi-angle α
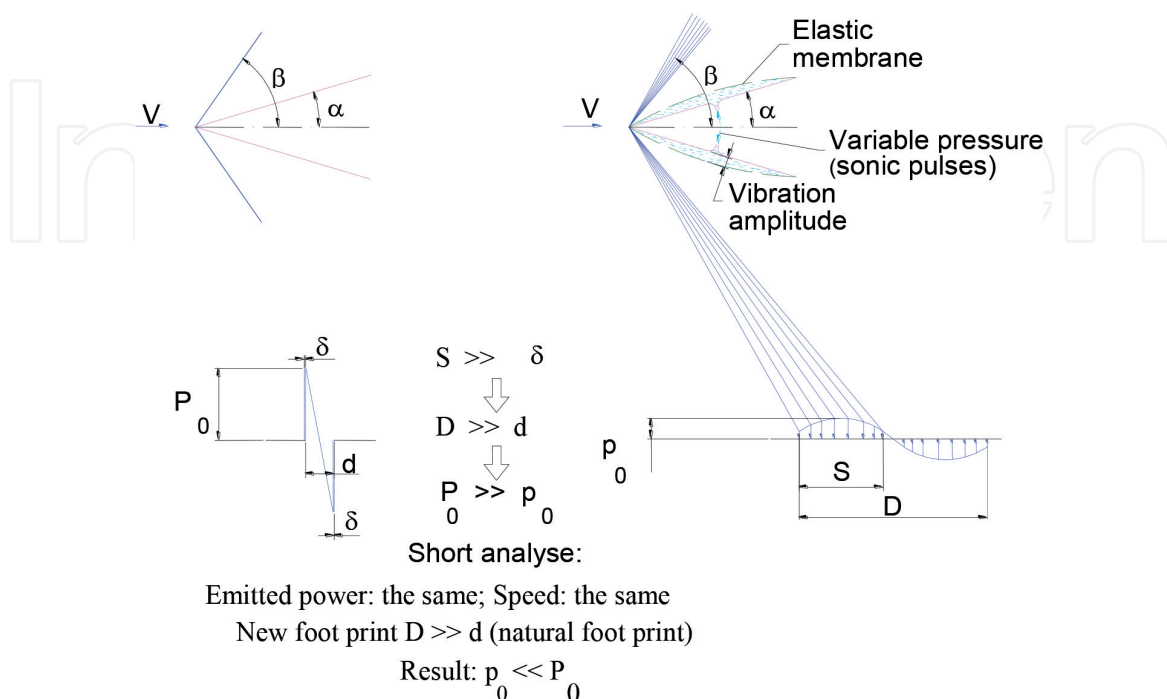

Figure 9.
Dispersion of shock wave by vibrating surfaces [26].

produces a large variation of semi-angle β. In the function of the Mach number, the variation of β can be even of several times larger than variation of α. This physical effect offers an important advantage: At the ground level, the dispersed shock wave extends on hundreds of meters. For example, if an aircraft is flying horizontally with speed M = 1.3, and the semi-angle of wing LE is α = 5°, the semi-angle β calculated with Eq. (1) is β = 59.96° [29]. If the semi-angle is α = 6°, the semi-angle β calculated with Eq. (1) is β = 63.46° [29]. So, if the variation of wedge semi-angle is Δα = 6° − 5° = 1°, the variation of semi-angle β is Δβ = 63.46° − 59.96° = 3.5°, i.e., much larger than Δα.

Assume M = 1.3, Δα = 1°, and Δβ = 3.5° (0.061 rad). If the aircraft is flying at height H = 15,000 m, shock wave dispersion is given by Eq. (2):

$$S = H \cdot \Delta\beta = 15000 \cdot 0.061 = 915 \, m \qquad (2)$$

If a supersonic aircraft has the length of 20 m, the natural ground footprint of the "N" wave is 40 m. One can easily see that through dispersion the footprint is enlarged about 23 times from 40 to 915 m.

However, even larger dispersion distances S can be obtained if through design the semi-angle α of wing LE is taken equally to α_{lim} for detaching of oblique shock wave. For a given supersonic cruise speed M, if the semi-angle α of wing LE is increased through vibration, only a little over α_{lim}, an extremely large variation of shock wave semi-angle β is produced. This is happening because when the semi-angle α is over α_{lim}, the oblique shock wave is detaching as presented in **Figure 10** [26].

The results of calculations using [29] are given in **Table 1**.

As it can be seen in **Table 1**, shock wave dispersion at the ground level is of thousands of meters.
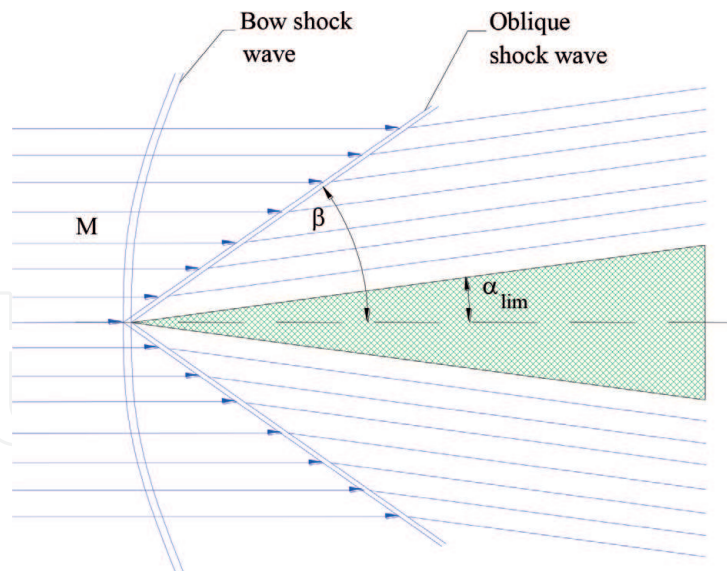

Figure 10.
Detaching of shock wave [26].

M	α_{lim} [°]	β_{before} [°]	β_{after} [°]	Δβ [°]	S [m]
1.300	6.650	68.59	90	21.41	5602
1.501	12.125	65.80	90	24.20	6332

Table 1.
Variation of β when α = α_{lim}.

For M = 1.501, if cone angle is α = 12.125°, a variation Δα = 0.025° theoretically produces transforming of oblique shock wave in a detached shock wave (bow shock wave).

Of course, keeping in control of such a process is a fine task, but it can be achieved if it is controlled by the aircraft onboard computer.

An important question is the following:

Which could be the most effective vibration frequency, ν? This is a difficult question. It is very clear that the effect of a low frequency, say 1 Hz, has no significant influence to shock wave dispersion because the vibration is too slow. Duration of a natural "N" wave is about 0.1 s. Probably, the period T of membrane oscillation should be smaller than 0.1 s, that is, the vibration frequency should be over $\nu = 1/T = 1/0.1s = 10$ Hz.

At this time there is no theory regarding how much could be this frequency. For this reason, experiments are the next necessary step. Some experiments having an acceptable price are presented at point 5.

4.3 Mechanical dispersion of shock wave using elastic fairings

Obviously, applying elastic membranes on aircraft nose and wing LE implies a difficult technology. Instead of that design, a new one can be seen in **Figures 11** and **12** [30]. This time the membrane is substituted by an elastic fairing made of thin carbon fiber composite fixed by the aircraft nose or wing LE. When the pressure in the air manifold varies (e.g., sinusoidal variation with frequency $\nu = 10$ Hz), local forces appear on elastic fairing determining its vibration. The variation of pressure must be equal to the resonance frequency of elastic fairing for obtaining the maximum vibration amplitude with a minimum pneumatic power.

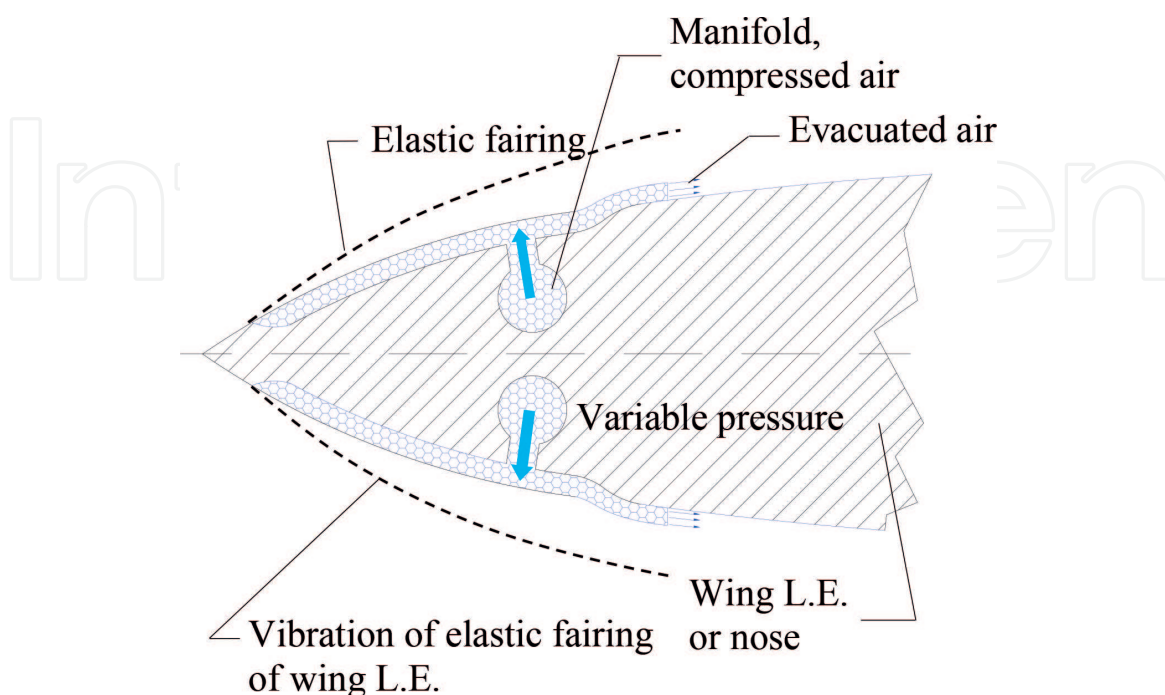Testing of such a solution has an acceptable price if the following two methods are applied.

Figure 11.
Principal scheme of shock wave dispersion through vibration of elastic fairings induced by compressed air [30].
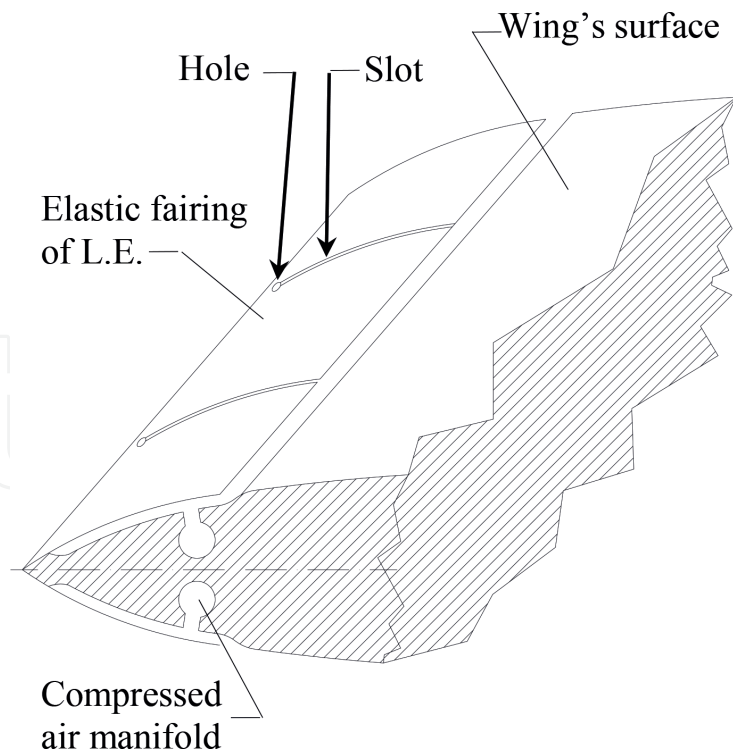
Figure 12.
View of a wing with elastic fairings at LE for dispersion of shock wave [30].

5. Proposed experimental tests for proving of concept

The effect of shock wave dispersion through mechanical vibrations can be tested in supersonic wind tunnel. At points 4.1 and 4.2, two test equipment are proposed.
The existing methods as schlieren photography are good for observing shock wave dispersion in supersonic wind tunnel.

5.1 The test equipment no. 1

At this equipment, a wedge composed of two elastic lamellae actuated by an electromagnet is used (see **Figure 13**) [26].
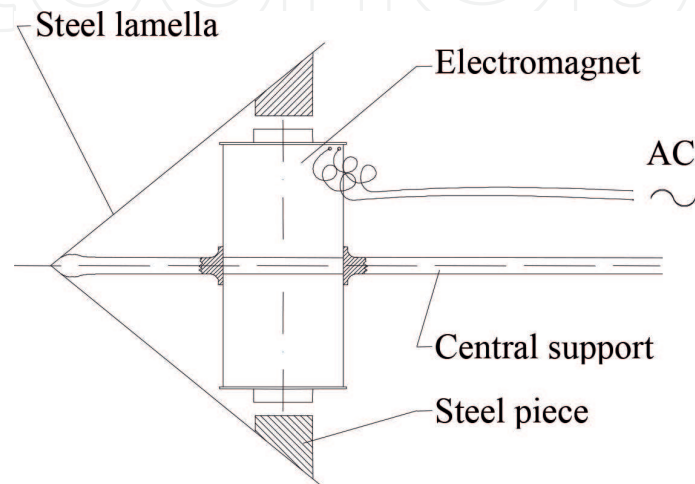
Figure 13.
The scheme of test equipment no. 1 [26].

The components of experimental equipment no. 1 are:

- Two steel lamellae having at their end steel pieces.

- Electromagnet that is fed by an alternative current (AC).

- Central support.

When electromagnet is powered with an alternative current at the frequency ν equal to the resonance frequency of lamella, the lamellae vibrate at the maximum amplitude. Vibration frequency can be changed if the mass of the two steel pieces is changed. When the weight of steel piece increases, the resonance frequency of lamella decreases and vice-versa. Another role of steel piece is to increase the attraction force of electromagnet on lamella.

Firstly, the shock wave is observed in the window of supersonic aerodynamic tunnel for various speeds when electromagnet is not actuated. The position of shock wave is schlieren photographed for various values of Mach number.

After that, the electromagnet is actuated by the AC having a frequency ν equally to the resonance frequency of lamella, and the shock wave is schlieren photographed for the same Mach number as before (when electromagnet was not actuated).

For every measurement, the shock wave should have variable taper and thickness, depending on vibration frequency and Mach number.

5.2 The test equipment no. 2

The test equipment no. 2 is more complex than test equipment no. 1. It should normally be used as a second step if good measurements are registered during using of equipment no. 1.

This equipment is presented in **Figure 14** [26]. The components of experimental equipment no. 2 are:

- Wedge simulating a cone or wing LE.

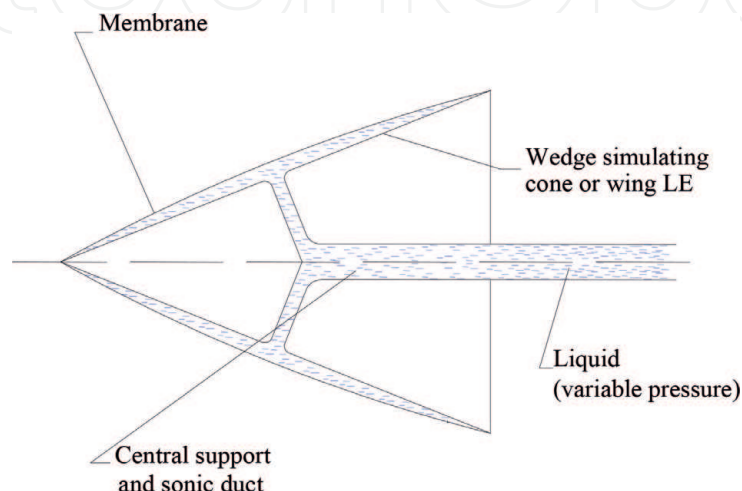- Membrane made of elastic material.

- Hydraulic liquid.

Figure 14.
Test equipment no. 2 [26].

A sonic generator sends pressure pulses to the main duct containing hydraulic liquid. The pressure pulses propagate with high speed to the liquid existent between membrane and wedge. As a result, membrane surface is bending and wedge angle increases with $\Delta\alpha$.

The experimenting procedure is similar to that presented at point 4.1: Firstly, the shock wave is observed for various speeds when sonic pulses through the main duct with hydraulic liquid are not present. Position of shock wave is schlieren photographed for various values of Mach number.

After that, sonic pulses are sent through the main duct with hydraulic liquid, and the shock wave is schlieren photographed for the same speeds as before.

For every measurement, the shock wave should have a variable taper and thickness depending on frequency and Mach number.

The experiments using the test equipment no. 2 are very useful because they simulate very close the real case on aircraft.

6. The supersonic European business and passenger aircraft

The European community intends to enter the competition for manufacturing of the future supersonic business and passenger aircraft. The future European supersonic aircraft could have a normal design except the nose and LE of wing and horizontal empennage. In a more sophisticated case, even the vertical empennage and the entry in engine admission device can be vibrated (**Figure 15** [26]). In the indicated areas, vibrating membranes or fairings should be mounted for shock wave dispersion.

7. Electrical solutions for dispersing of shock wave

Intense research is taking place in our days for dispersion of shock waves generated by aircraft through electrical means. It was observed that the so called plasma actuators consisting of high voltage electrodes (cathodes and anodes) have effect on airflow through air ionization. At present plasma actuators are researched both for noise reduction in the fan ducts of jet engines and for dispersion of shock wave for mitigation of its effects at ground level.

7.1 Using of plasma actuators for dispersion of shock wave

In some preliminary experiments, plasma actuators (**Figure 16**) were used for increasing of semi-angle β of conical shock wave (**Figure 16b**) [31].

When the potential difference between two electrodes (cathode, anode) (**Figure 16a**) is increasing progressively, the cone semi-angle β (**Figure 16b**) is increasing to a critical value β_{cr} when the shock wave becomes detached (**Figure 17**,
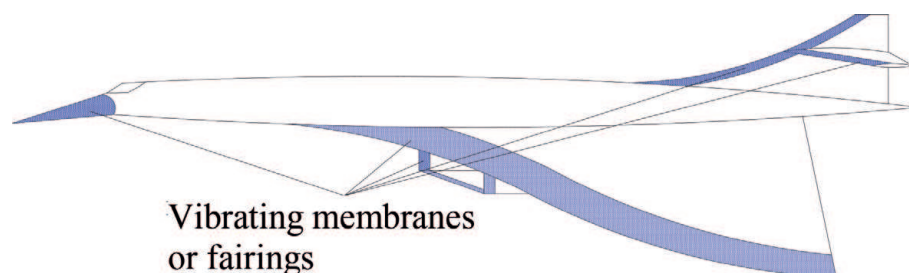

Figure 15.
A possible European supersonic business jet/passenger aircraft using vibrating surfaces for shock wave dispersion [26].
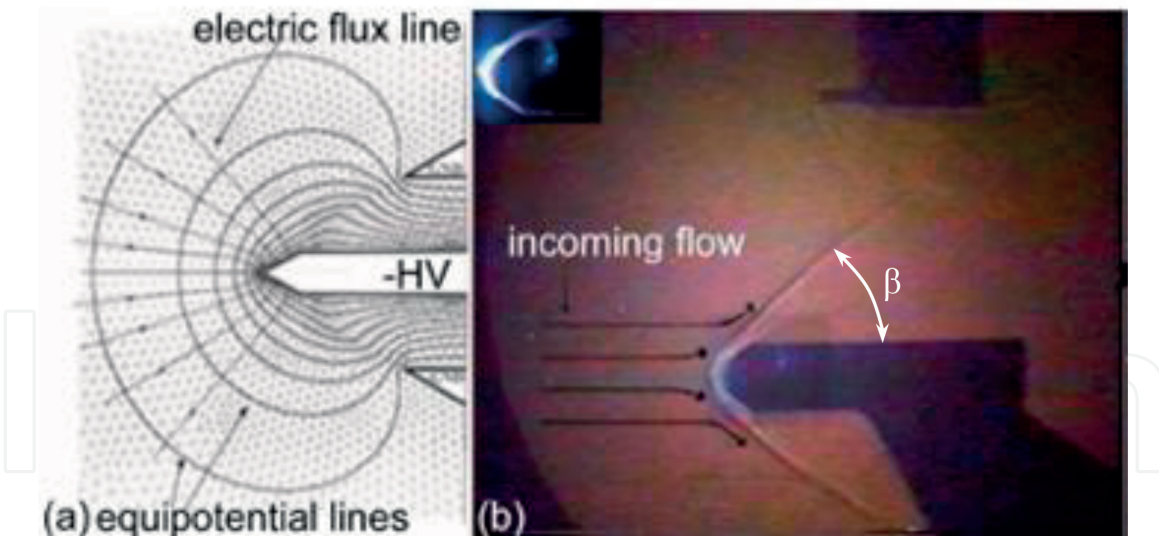
Figure 16.
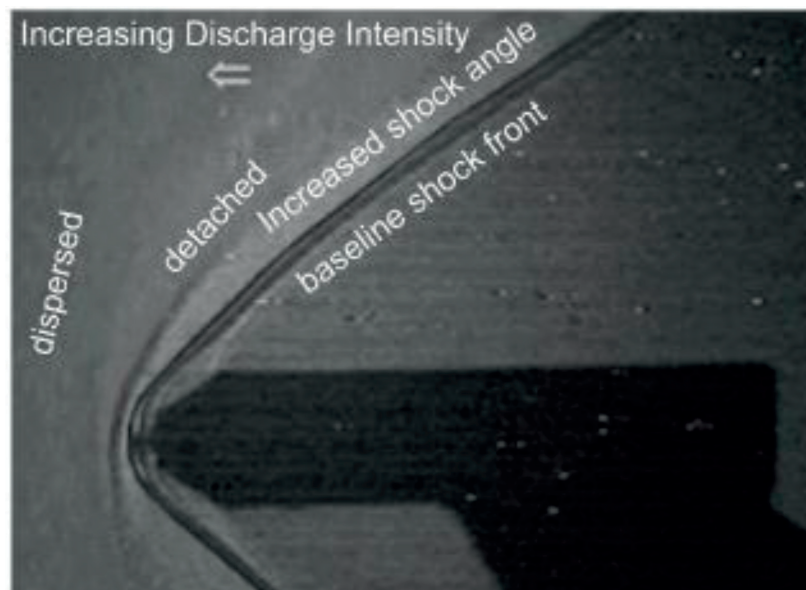*Dispersing of shock wave using plasma actuators [31].*

Figure 17.
Detaching of shock wave for a given potential [31].

Taylor-Maccoll theory). The potential difference between the two electrodes is of several thousands of volts.

In the presented case, positive ions are generated when atoms are losing an electron. An avalanche effect is taking place when electromagnetic energy is ionizing more atoms (this effect is visible as a blue light). Applying of such a solution seems to be difficult in the case of real aircraft because the electrical discharge can become thermal destroying in this way the electrode surfaces.

On the other hand, the aircraft nose and wing LE have a large area, and it is hard to believe that such a system, which was tested at low scale can be applied at the large scale of an aircraft.

7.2 A new possible solution for shock wave dispersing through injection of electrons in surrounding airflow through sharp electrodes

The new possible solution proposed in this paper is based on a massive injection of electrons through very fine and sharp electrodes in the upstream of air stream (in

front of aircraft). This solution could be applied in future at the new supersonic jet called Concorde Mark 2 (**Figure 18** [32]).

The supersonic passenger aircraft Concorde Mark 2 filled in patent [33] by Astrium SAS and European Aeronautic Defense and Space Company would be capable to fly with 4023 km/h (1118 m/s) transporting 20 passengers or 3 tons of cargo on a distance of 8851 km. The duration of travel between London and New York would be of 1 hour.

The cathodes are sharp Wolfram needles placed along a rod, which is fixed in the tip of aircraft nose and along the wing LE (**Figure 18**). The anodes are thin copper sheets, which are fixed by the aircraft nose and pressure/suction sides of wing. Obviously, the anodes and cathodes are electrically insulated by the aircraft frame.

[Note: In **Figure 18**, the dimensions of cathodes are exaggerated for clarity. Actually, they have the dimension of a usual sewing needle].

The system works as follows:

A high potential electrical source (thousands of volts) is connected to the cathodes and anodes by means of an electrically insulated wire network. When the electrical high voltage source is connected to the wire network, a high number of electrons are released through the sharp tips of the cathodes.

[Note: This type of discharge differs by the type of discharge presented in Chapter 6.1 where positive ions are generated through loosing of electrons by atoms due to the primary electrons generated by cathode and accelerated by the potential difference between the cathode and anode].

The released electros are spread in the air stream without generating a significant number of ions because the distance between cathodes and anodes is much larger than in the case of plasma actuators.

The quantity of electrons injected in air stream is very high due to the high number of cathodes and their sharpness and the high potential applied. After detaching the sharp cathodes, the electrons move together with the oxygen and nitrogen molecules to the shock wave, which has the semi-angle β given by Eq. (1) (in the case of oblique shock wave). The injected electrons can be free among the oxygen and nitrogen molecules or can be temporary attached by a part of molecules generating in this way temporary negative molecules.

In this way, the shock wave will be composed of neutral nitrogen and oxygen molecules, free electrons and temporary negative molecules. The shock wave is
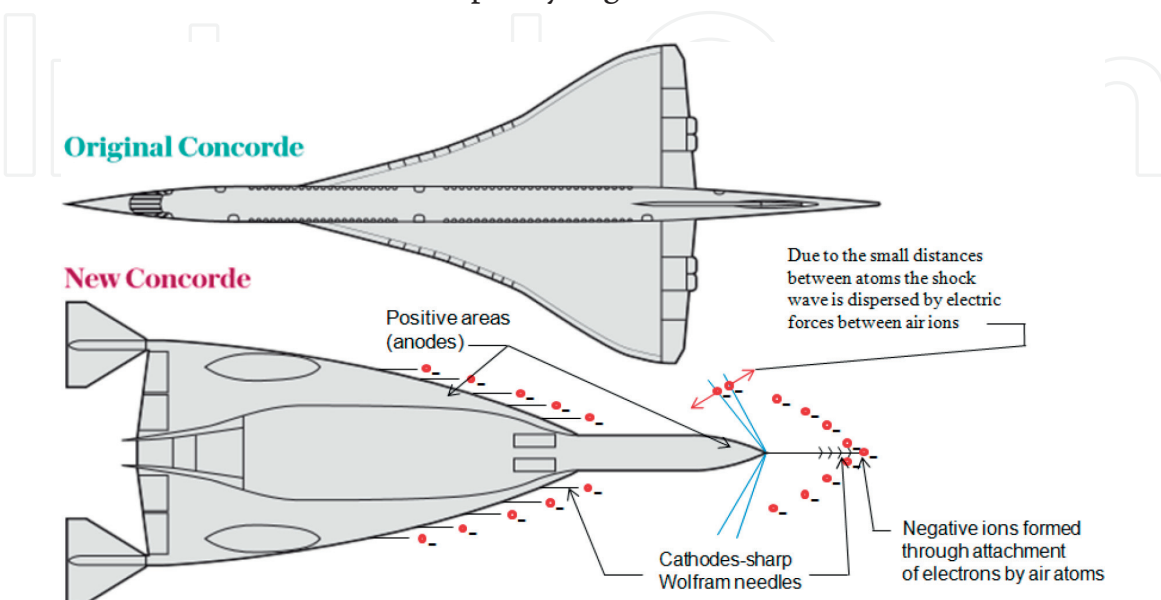

Figure 18.
New solution proposed for dispersing of shock wave through injection of electrons in surrounding airflow by sharp electrodes [16, 32, 33].

extremely thin (**Figure 7**, [27]). Inside the shock wave, due to the very small space, the density of electrons and temporary negative molecules is high. As a result, due to electrostatic repelling forces, the shock wave thickness must increase, and its impact at ground level will be mitigated.

After passing through the shock wave, the airstream is neutralized by the anodes placed on the aircraft nose and wing, which collect the electrons present in the air stream.

Due to the very high complexity of phenomena, it is risky to make theoretical predictions at this time. The best methodology is to do experiments in a supersonic wind tunnel using various configurations of electrodes connected at high potentials for observing shock wave shape. The shock wave should become weaker similar to the image presented in **Figure 17**. In that case, the significance will be that impact of sonic boom at ground level is mitigated in comparison with the normal case.

If the present system applied at Concorde Mark 2 will be the case, it should be activated in ascending and descending phase when the impact of sonic boom on community is maximum. When the aircraft is flying at very high heights or over the ocean, activation of system is not necessary.

8. Conclusions

The new solutions presented in this chapter use dispersion of shock wave through mechanical or electrical means. These solutions are alternatives for "shaping" solution or using of very thin fuselage.

Following the shock wave dispersion, the resulting sonic boom is spread on a much larger area at the ground level, as a consequence, the air in the 'N' shock wave is much smaller than in the normal case.

Low amplitude mechanical vibration of aircraft nose, wing LE, and horizontal empennage LE leads to shock wave dispersion.

A first technological possibility is vibrating a membrane, which is stretched over aircraft nose, wing LE, and horizontal empennage LE. In this case, the membranes are actuated by sonic pulses propagated through a hydraulic liquid.

A second solution is vibrating of elastic fairings placed over the aircraft nose, wing LE, and horizontal empennage LE.

Injection of electrons in front of aircraft cone/wing/empennage could be a productive technology for reduction of sonic boom impact on community in the case of supersonic/hypersonic passenger aircraft and business jets.

The cathode (negative electrode) is composed of multiple needles of Wolfram placed on a rod, which is fixed in the tip of aircraft cone or placed along the leading edges of wing and horizontal tail.

The anode (positive electrode) is composed of multiple copper plates glued by aircraft nose and wing suction/pressure sides.

The cathodes and anodes are electrically insulated by the aircraft frame.

The electrons released by the sharp cathodes in the airstream are free or can be attached by oxygen and nitrogen molecules forming temporary negative molecules.

When arriving in the shock wave, these temporary negative molecules and free electrons repel each other dispersing the shock wave. As a result, the impact of "N" shock wave at ground level will be much reduced.

Experiments should be initiated for evaluation of this possible effect. Voltages of many thousands of V should be used because the number of electrons injected in the air stream depends on the value of potential difference between the cathodes and anodes.

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The original solutions presented in this chapter were filed in patent.

Conflict of interest

Declaration: There is no conflict of interest related by scientific information presented in this Chapter.

Nomenclature

d	the length of natural foot print of sonic boom, m
D	the footprint length of the extended "N" wave of sonic boom when vibration is applied, m
H	the flight altitude of aircraft, m
M	Mach number, dimensionless
P_0	the maximum pressure of the natural "N" wave of sonic boom, Pa
p_0	the maximum pressure of the extended "N" wave of sonic boom when vibration is applied, Pa
S	the enlarged thickness of shock wave at ground level due to vibration, m
T	vibration period, s

Greek:

δ	the natural thickness of shock wave, m
ν	the vibration frequency of shock wave, s^{-1}

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