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The Concept of Active Voice Reduction using Multipole Secondary Source: Case Study of C-150 Aircraft

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Abstract—**In order to protect residents living around the airport from aircraft noise disturbance, regulations have been set for the maximum permissible noise level limit. One of the international regulations that regulate the limits of aircraft exterior noise levels is the Federal Aviation Regulation (FAR) part 36 of the United States Regulatory Agency, or the Civil Aviation Safety Regulation (CASR) part 36 of the national regulatory agency. In addition, for military purposes, observer planes are also needed with the lowest possible sound level such that they will not attract the enemy's attention. This paper contains the concept of active exterior sound control/elimination with an unconventional secondary source method (anti-noise), using the multipole secondary source method. Multipole secondary sources are developed based on Taylor series expansion to obtain higher order secondary sources, such as dipoles, quadrupoles, octopoles, and so on, which are used for noise canceling. A significant noise reduction can be obtained by using a high-order secondary source and by optimizing the power of the secondary source. Numerical simulation of noise reduction in the free field was carried out by this method. The simulation results show that noise reduction reaches 50 dB at 200 Hz. The method, which is still a concept, was then used to simulate noise reduction on a Cessna-150 aircraft.**

Index Terms—**active voice reduction, multipole secondary source, aircraft**

I. INTRODUCTION

NOISE problems on airplanes are divided into two: exterior noise and interior noise. Exterior noise is a noise generated by the aircraft to the environment outside the aircraft. And, interior noise is a noise in the aircraft cabin that is felt by passengers and crews.

Exterior noise is related to regulation, while interior noise does not have regulations that must be met. However, it affects passenger comfort. Exterior noise can be a problem that can cause environmental nuisance and can cause the commercial failure of an aircraft product. For example, the Concorde aircraft produces a relatively loud noise, making the aircraft less attractive to the market due to environmental reasons. As for unmanned aircraft for military purposes, some missions require a reconnaissance aircraft specification that does not even make a sound, such that it will not be detected by the enemy that is being scouted.

With regard to the things mentioned above, the commercial feasibility of active sound reduction is very promising. In some cases, active noise control is more economical and more effective in reducing noise than passive noise control. Furthermore, active noise cancellation can also selectively reduce noise. Active noise reduction using conventional secondary sources can be very complicated when significant noise reduction is desired, as multiple secondary source positions are required. Active noise cancellation is also less effective at reducing high-frequency noise.

In this paper, we present the use of multipole secondary sources to overcome the aforementioned problem. Then the secondary multipole source will be used to perform a numerical simulation of noise reduction on a Cessna 150 aircraft. The noise reduction simulation assumes that the noise source is supposed to come from a single point. This assumption is still acceptable if the highest frequency to be reduced is not too high.

Although the concept of a multipole secondary source derived using the Taylor series is well known, the use of a multipole secondary source to actively eliminate sound still encounters several obstacles. These obstacles include the impossibility of using a multipole secondary source of infinite order. To overcome this problem, optimization of the secondary source power should be carried out so that minimal sound power is obtained in the sound field. With this optimization, it will be shown that it is still possible to reduce noise efficiently with a limited multipole order.

II. ELEMENTARY AEROACOUSTIC SOURCES

A. Monopole Sources

The monopole acoustic source is described as a sphere of radius a, vibrating in the radial direction. Assuming that the vibration of the monopole source is harmonic, then:

$$v_{r=a} = v_0 e^{i\omega t} \tag{1}$$

where v_0 is the surface velocity amplitude. Thus, the sound pressure and velocity potential produced by the monopole source are:

$$p'(r,t) = \frac{A}{r} e^{i\omega(t-r/c)} \tag{2}$$

$$\phi_m(r,t) = \frac{i}{\rho_\infty \omega}\frac{A}{r} e^{i\omega(t-r/c)} \tag{3}$$

where,

$$A = -\frac{\rho_\infty \omega v_0 a^2 e^{i\omega a/c}}{i(1+i\frac{\omega a}{c})} \tag{4}$$

Substituting equation (4) into (3), and the result is applied to the free field (r >> a), we will have:

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$$\phi_m(r,t) = -\frac{v_0 a^2}{(1+i\frac{\omega a}{c})}\frac{1}{r}e^{i\omega(t-r/c)} \quad (5)$$

This equation shows that the monopole source produces a uni-directional waveform. The particle oscillation velocity in the radial direction is obtained by deriving equation (5) with respect to r:

$$v_r(r,t) = \frac{\partial\phi_m}{\partial r} = v_0\frac{a}{r}\frac{i\frac{\omega a}{c}}{\left(1+i\frac{\omega a}{c}\right)}\left(1+\frac{c}{i\omega r}\right)e^{i\omega(t-r/c)} \quad (6)$$

The intensity and power of the sound due to the monopole source are:

$$I(r) = \frac{1}{T}\int_0^T p'v_r dt = \frac{\rho_\infty v_0^2 a^4\omega^2}{2cr^2}\frac{1}{\sqrt{1+\left(\frac{\omega a}{c}\right)^2}} \quad (7)$$

$$W = I(r)4\pi r^2 = \frac{2\pi\rho_\infty v_0^2 a^4\omega^2}{c}\frac{1}{\sqrt{1+\left(\frac{\omega a}{c}\right)^2}} \quad (8)$$

For a monopole source which is a point source ($\omega a/c << 1$), then from equation (5), we obtain:

$$\phi_m(r,t) = -\frac{Q_0}{\rho_\infty 4\pi r}e^{i\omega(t-r/c)} \quad (9)$$

where $Q_0 e^{i\omega(t-r/c)}$ = Q(t) is the mass flow per unit time produced by the monopole sound source. Therefore, the sound pressure becomes:

$$p'(r,t) = -\rho_\infty\frac{\partial\phi_m}{\partial t} = \frac{1}{4\pi r}\frac{\partial}{\partial t}\left[Q_0 e^{i\omega(t-r/c)}\right] \quad (10)$$

Equations (9) and (10) show the existence of a singularity at r = 0. Hence, the above equation only applies to areas outside the monopole source.

To express the sound field around the value of r = 0, we use the property that the wave equation approaches Laplace's equation if r approaches 0:

$$\lim_{r\to 0}\left[\nabla^2\phi_m - \frac{1}{c^2}\frac{\partial^2\phi_m}{\partial r^2}\right] = \nabla^2\phi_m \quad (11)$$

For points close to r = 0, the wave equation can be approximated by:

$$\nabla^2\phi_m = \nabla.(\nabla\phi_m) = 0 \quad (12)$$

According to the divergence theorem or Green's theorem, the integral of the divergence over the entire volume of the sphere is equal to the radial gradient which is integrated along the surface of the sphere:

$$\int_V \nabla.(\nabla\phi_m)dV = \int\frac{\partial\phi_m}{\partial_n}dS \quad (13)$$

With equation (9), the right part of the equation (13) can be written as:

$$\int_S\frac{\partial}{\partial_n}\left[-\frac{Q_0}{\rho_\infty 4\pi r}e^{i\omega(t-r/c)}\right]dS$$
$$= \left[\frac{Q_0}{\rho_\infty 4\pi r^2}e^{i\omega(t-r/c)} + -\frac{Q_0}{\rho_\infty 4\pi r}e^{i\omega(t-r/c)}\frac{i\omega}{c}\right]4\pi r^2$$
$$= \left[\frac{1}{\rho_\infty}Q_0 + \frac{r}{\rho_\infty}Q_0\frac{i\omega}{c}\right]e^{i\omega(t-r/c)} \quad (14)$$

For the r limit close to 0, we get:

$$\int_S\frac{\partial\phi_m}{\partial_n}dS = \frac{1}{\rho_\infty}Q_0 e^{i\omega t} \quad (15)$$

By comparing these results with equations (11) and (13), we obtain:

$$\int_V\left[\nabla^2\phi_m - \frac{1}{c^2}\frac{\partial^2\phi_m}{\partial r^2}\right]dV = \frac{1}{\rho_\infty}Q_0 e^{i\omega t} \quad (16)$$

To ensure that the right side of equation (16) is equal to 0 for all places, except at the point r = 0, the delta function is used. For values near r = 0, the delta function has a large value so that the integral along the volume V surrounding r = 0 is one:

$$\int_V \delta(r)dV = 1 \quad (17)$$

On the other hand, due to the nature of the delta function, the integral value = 0 if V is outside r = 0. Hence, the right side of equation (16) can be expressed as:

$$\frac{1}{\rho_\infty}Q_0 e^{i\omega t} = \int_V\frac{1}{\rho_\infty}Q_0 e^{i\omega t}\delta(r)dV \quad (18)$$

If equation (18) is substituted in (16), then we get:

$$\nabla^2\phi_m - \frac{1}{c^2}\frac{\partial^2\phi_m}{\partial r^2} = \frac{1}{\rho_\infty}Q_0 e^{i\omega t}\delta(r) \quad (19)$$

The right-hand side of equation (19) represents the source of the monopole point.

B. Dipole Sources

The dipole source is modeled as a monopole source with radius a with density ρ_∞ and oscillates along the axis Z. In the case where the ball produces harmonic motion, then:

$$w = w_0 e^{i\omega t}. \quad (20)$$

To get the dipole velocity potential, ϕ_d, we use:

$$\frac{\partial}{\partial z}\left[\nabla^2\phi_m - \frac{1}{c^2}\frac{\partial^2\phi_m}{\partial r^2}\right] = \nabla^2\left[\frac{\partial\phi_m}{\partial z}\right] - \frac{1}{c^2}\frac{\partial^2\phi_m}{\partial t^2}\left[\frac{\partial\phi_m}{\partial z}\right] = 0 \quad (21)$$

where only the required solution will be used.
In polar coordinate form it can be written as:

$$\frac{\partial}{\partial z}(\phi_m) = \cos\frac{\partial\phi_m}{\partial r} = \phi_d. \quad (22)$$

By substituting equation (3) into (22) and then derived from *r*, we get:

$$\phi_d(\theta,r,t) = -\frac{\cos\theta a^3 w_0\left(1+i\frac{\omega r}{c}\right)}{2r^2\left[1+i\frac{\omega a}{c}-\frac{1}{2}\left(\frac{\omega a}{c}\right)^2\right]}e^{i\omega(t-r/c)} \quad (23)$$

For the case of the dipole source being a point, then $\omega a / c << 1$, and equation (23) becomes:

$$\phi_d(\theta, r, t) = -\cos\theta \frac{a^3 w_0}{2r^2}\left(1 + i\frac{\omega r}{c}\right)e^{i\omega(t-r/c)} \tag{24}$$

Using equation (24), the sound pressure and the radial velocity of the particle are expressed by:

$$p'(\theta, r, t) = -\rho_\infty \frac{\partial \phi_t}{\partial t} = \rho_\infty \cos\theta \frac{a^3 w_0}{2r^2}\left(1 + i\frac{\omega r}{c}\right)e^{i\omega(t-r/c)} i\omega \tag{25}$$

$$v_r(\theta, r, t) = \frac{\partial \phi_d}{\partial r} = \cos\theta \frac{a^3 w_0}{2r^2}\left(\frac{2}{r} + i\frac{2\omega}{c} - \frac{\omega^2 r}{c^2}\right)e^{i\omega(t-r/c)} \tag{26}$$

Equations (25) and (26) show that the sound pressure and the radial particle velocity are functions of cos θ. With the functions of cos θ, then the pressure and speed of sound will be maximum along the Z axis and is zero at an angle of 900 to the Z axis.

C. Quadrupole Sources

Quadrupole source analysis was developed using dipole sources placed side by side. The sound pressure at point p(x,y,z) generated by the quadrupole source is the sum of the two dipole sources, thus:

$$p'(x, y, z, t) = p_1'(x, y, z, t) + p_2'(x, y, z, t) \tag{27}$$

p_2' in the equation (27) can be expressed as:

$$p_2'(x, y, z, t) = p_2'(x + \frac{\lambda}{2}, y, z, t) - \frac{\lambda}{2}\frac{\partial p_2'}{\partial x} \tag{28}$$

The magnitude of the pressure at the point p' $(x + \lambda/2, y, z)$, generated by the dipole at the point $x = \lambda/2, y = 0, z = 0$, is:

$$p_2'(x + \frac{\lambda}{2}, y, z, t) = -p_1'(x, y, z, t) \tag{29}$$

Combining equations (28) and (29) gives:

$$p_2'(x, y, z, t) = -\left[p_1'(x, y, z, t) - \frac{\lambda}{2}\frac{\partial p_1'}{\partial x}\right] \tag{30}$$

Substituting the equation into (27), results in:

$$p'(x, y, z, t) = \frac{\lambda}{2}\frac{\partial p_1'}{\partial x} \tag{31}$$

It can be seen that the quadrupole sound field is formed by two dipole sources that have opposite source strengths but are placed in places that are not close together, such that they do not cancel each other out.

The dipole velocity potential is the partial derivative of the monopole velocity potential in the direction of the dipole axis. The sound pressure produced by the quadrupole source is the partial derivative of the dipole sound pressure with respect to the z coordinate, so that:

$$p'(x, y, z, t) = -\frac{\lambda}{2}\frac{F_0}{4\pi}\frac{\partial'}{\partial x}\left[\cos\theta \frac{\partial}{\partial r} e^{i\omega(t-r/c)}\right]$$

$$= \frac{i\omega}{c}\frac{\lambda}{2}\frac{F_0}{4\pi}\frac{\partial'}{\partial x}\left[\frac{\cos\theta e^{i\omega(t-r/c)}}{r}\right] \tag{32}$$

The sound intensity due to the quadrupole source is:

$$I(r, \theta) = \frac{[p_e(r, \theta)]^2}{\rho_\infty c} \propto \rho_\infty \frac{\lambda^2}{r^2}\frac{w^8}{c^5}(\sin 2\theta)^2 \tag{33}$$

Acoustic power is obtained by integrating the sound intensity along the entire surface of the sphere. Therefore:

$$W \propto \rho_\infty \lambda^2 \frac{w^8}{c^5} \tag{34}$$

III. SOUND REDUCTION CONCEPT WITH MULTIPOLE SECONDARY SOURCE

The concept of noise reduction using a multipole secondary source was first developed by Kempton employing a Taylor series which is used to represent a monopole source by a multipole. Each analytical function, g(x), can be expressed in terms of a Taylor series as follows:

$$g(x + h) = \sum_{n=0}^{\infty} \frac{h^n}{n!}\frac{\partial^n}{\partial x^n} g(x) , \tag{35}$$

where h is the incremental of the variable x. The above formulation will converge to the region $|x| > |h|$.

Kempton used these results to show that the sound pressure field of a monopole source located at the -h point on the x-axis can be expressed as an infinite-order multipole point field located at the center of the coordinate system. Figure 1 shows the geometry and coordinate system used in this case.

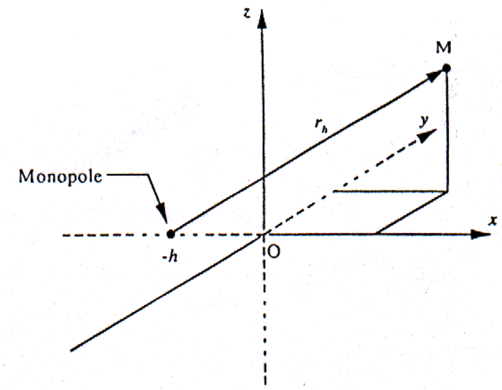

Fig. 1. Geometry and coordinate system model.

The sound pressure at point M (which has coordinates x, y and z) due to the monopole primary source placed at – h on the x-axis, can be expressed by the equation:

$$P_{pm}(x, y, z) = \frac{j\omega\rho}{4\pi} Q_{pm} \frac{e^{-jkr_h}}{r_h} \tag{36}$$

where Q_{pm} is the power of the monopole primary source, $r_h = \sqrt{(x+h)^2 + y^2 + z^2}$, ρ is the outer air density, $\omega = 2\pi f$ where f is the frequency, $k = \omega / c$ where c is the sound velocity, and $j = \sqrt{-1}$. Note that sign convention $e^{+j\omega t}$ should be priorly determined. If the right-hand side of equation (36) is expanded in the Taylor series, it becomes:

$$P_{pm}(x,y,z) = \frac{j\omega\rho}{4\pi}\sum_{n=0}^{\infty} Q_{pm}\frac{h^n}{n!}\frac{\partial^n}{\partial x^n}\left(\frac{e^{-jkr}}{r}\right) \quad (37)$$

where $r = \sqrt{x^2 + y^2 + z^2}$. It can be shown that for n = 0, $\left(j\omega\rho/4\pi\right)Q_{pm}\left(e^{-jkr}/r\right)$ is the sound pressure field formed by the monopole point located at the center of the coordinate system. In the same way, for n=l, $\left(j\omega\rho/4\pi\right)Q_{pm}h\left(\partial/\partial x\right)\left(e^{-jkr}/r\right)$ represents the sound pressure field formed by a dipole point located at the center and directed along the x-axis. So, the general form $\left(j\omega\rho/4\pi\right)Q_{pm}\left(h^n/n!\right)\left(\partial^n/\partial x^n\right)\left(e^{-jkr}/r\right)$ represents the n-order longitudinal multipole field component that runs along the x-axis and lies at the center of the coordinate system (it should be noted that monopoles are defined here as sources of order 0).

It can be seen in equation (37) that the sound pressure field produced by a monopole placed at –h on the x-axis can be generated with an infinitely-order multipole point, which is located at the center of the coordinate system. Thus, if the multipole characterized by equation (37) is placed at the center point, and then operated with the opposite phase to the primary source, then each field point that lies outside the sphere with a radius $|h|$ will be eliminated.

In general, the monopole primary sound field can be expressed explicitly in terms of the power of the multipole source:

$$P_{pm}(x,y,z) = \frac{j\omega\rho}{4\pi}\sum_{n=0}^{\infty} Q_{sn}\frac{\partial^n}{\partial x^n}\left(\frac{e^{-jkr}}{r}\right) \quad (38)$$

The power of the multipole source in the equation (38), Q_{sn}, can be made by comparing with equation (37) if the power of the monopole primary source, Q_{pm}, and the secondary source distance, h, are both predetermined. It can be seen that the monopole order in the Taylor series expansion has the same source power as the monopole primary source power, that is, $Q_{s0} = Q_{pm}$. The dipole secondary source has a source power of $Q_{s1} = hQ_{pm}$, and, in general form, The nth order multipole component has source power $Q_{sn} = h^n Q_{pm}/n!$. This approach is used to define the power of secondary sources, hereinafter referred to as the direct approach.

Q_{sn} is the source power required to produce an exact monopole primary sound pressure field if the Taylor series expansion equations (37) and (38) are solved in infinite form. At the time of implementation, it is not possible to create a multipole with infinite order, so the series must be truncated. If only a limited number of multipole components can be used, Q_{sn} obtained by direct approximation does not result in optimal elimination of the monopole primary field. For this reason, it is recommended to optimize the source power, which can minimize the total sound power. Simulation of sound reduction with secondary source power without optimization can be seen in Figure 2, while the simulation with optimization can be seen in Figure 3.

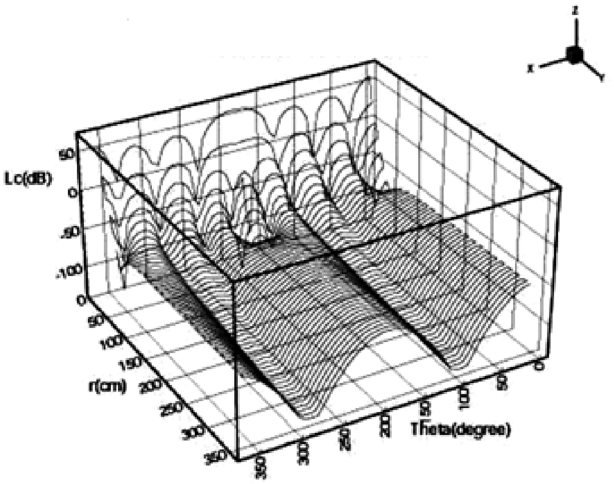

Fig. 2. Simulation of sound reduction as a function of theta and direct approach distance, *n=3*.

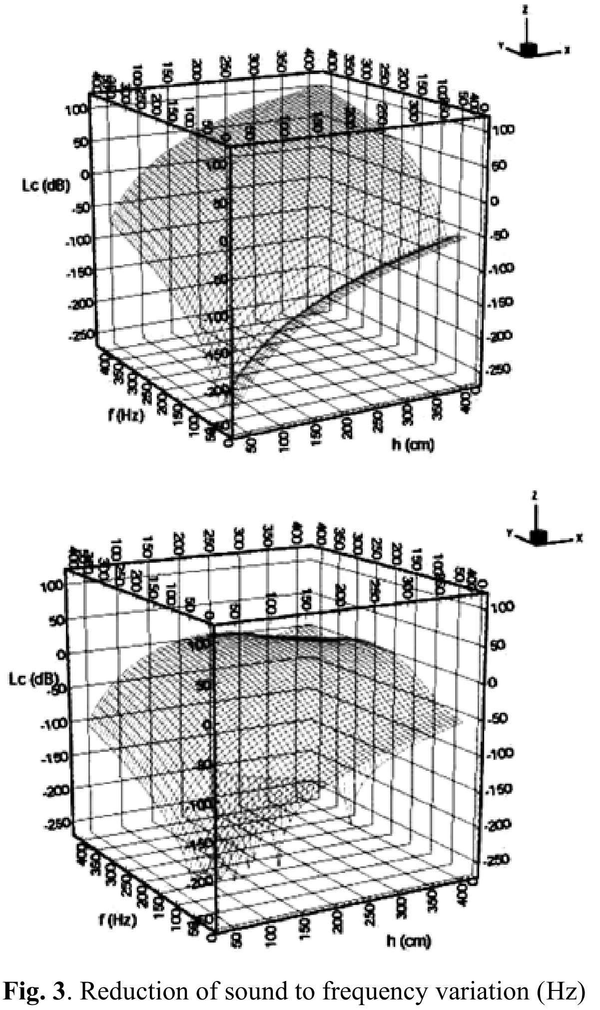

Fig. 3. Reduction of sound to frequency variation (Hz) and distance from primary source to secondary source (cm) without optimization (top) and with optimization (bottom).

IV. NUMERICAL SIMULATION OF NOISE REDUCTION USING A MULTIPOLE SECONDARY SOURCE ON A C-150 AIRCRAFT

In the following section, the results of noise reduction from the Cessna 150 aircraft engine are presented. The Cessna 150 aircraft belongs to the category of small aircraft that use a propeller engine. Figure 4 is a graph of sound pressure in the time domain obtained by measuring aircraft noise. Measurements were made on the condition that the aircraft was on the ground. Figure 5 shows the response of the aircraft engine noise frequency.

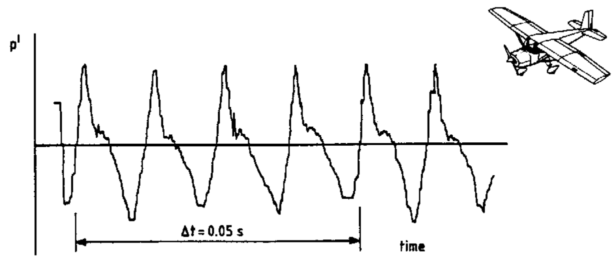

Fig. 4. C-150 aircraft illustration and response time diagram.

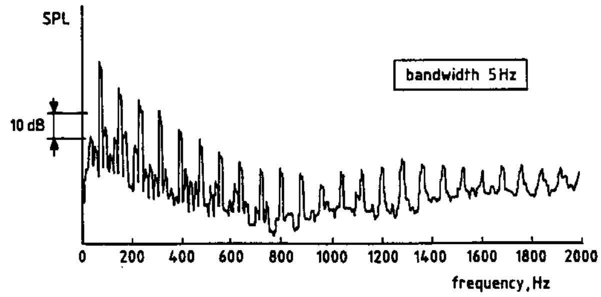

Fig. 5. Spectrum of C-150 aircraft noise frequency.

The Cessna 150 is single-engine and has a two-blade propeller driven by a four-cylinder piston engine. The peaks in the frequency response (Figure 5) correspond to the frequency due to the propeller blades' rotation and the piston engine's combustion frequency. The magnitude of the resulting frequency due to the rotation of the propeller blade, f_1, is expressed by:

$$f_1 = B\frac{n_p}{60}, \text{Hz} \tag{39}$$

where B denotes the number of propeller blades and n_p is the rotational speed of the propeller in rpm. On the aircraft under review B=2 and n_p = 2400 rpm, thus;

$$f_1 = 2\frac{2400}{60} = 80\,\text{Hz} \tag{40}$$

Because the aircraft engine is a 4-stroke engine, the frequency due to combustion, f_e, is expressed by:

$$f_e = N\frac{n/2}{60}, \text{Hz} \tag{41}$$

where N is the number of cylinders and n is the engine speed in rpm.

With N=4 and $n = n_p = 2400$ rpm, we obtain $f_e = f_1$.

Since $f_e = f_1$, then the noise contribution due to the propeller and due to the engine cannot be separated in the frequency spectrum.

Figure 6 shows a numerical simulation of noise reduction that can be achieved on a C-150 aircraft using a multipole secondary source for various maximum frequencies to be reduced.

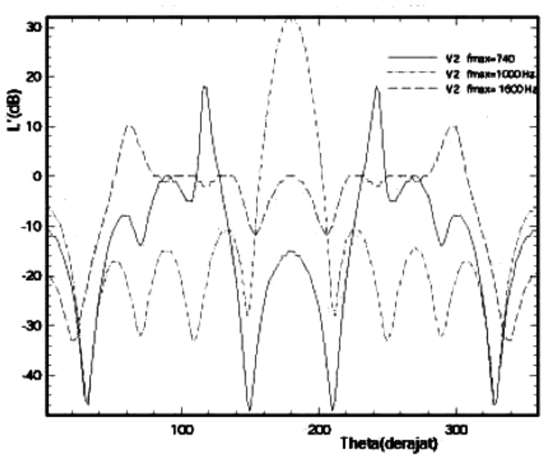

Fig. 6. Numerical simulation results of C-150 aircraft engine noise reduction.

These results are obtained with the assumption that the noise source is located at one point. The distance from the noise source to the anti-noise source is quite close (15 cm). The data used for the calculations were obtained from reference books [7].

V. IMPLEMENTATION PROJECTION

On-line implementation of active noise reduction in aircraft using multipole secondary sources is still a long way to go. Therefore, the following paper presents only the implementation projections. Implementing active noise reduction on the C-150 aircraft is very suitable due to the periodic noise waveform, which requires no strict feedback. The following are the steps taken to implement noise cancellation using a multipole secondary source.

A. Multipole Secondary Source Setup

While monopole sound is produced using one monopole speaker, dipole sound is produced by placing monopole speakers side by side, where one speaker is in the opposite phase from the other one. Then, quadrupole sound is produced by placing dipole sources side by side, and so on. Procurement of multipole secondary sources requires seven monopole speakers to reach quadrupole order. Figure 7 shows the system layout that will be used for the implementation.

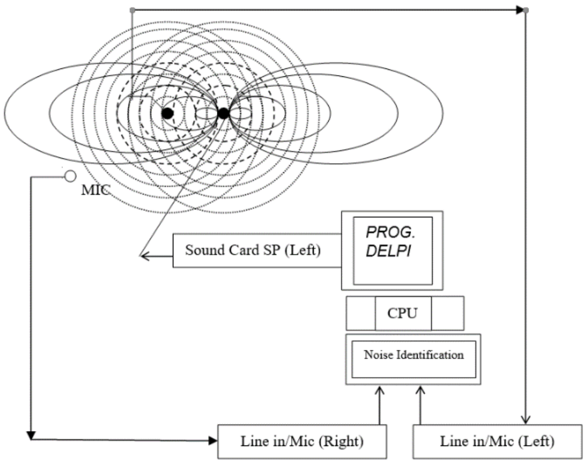

Fig. 7. Projected schematic of noise reduction implementation on C-150 aircraft.

The way the above system works is as follows. First, the noise is sensed by the sensor. The sensor might be a microphone sensor or a vibration sensor. The advantage of using a vibration sensor (accelerometer) is that we immediately know the noise source. However, if we use a microphone, we have to do the inverse process to find out the noise source from the noise sensed in the sound field.

Figure 8 is a sound signal reconstruction of the C-150 aircraft noise. The data is taken from t=0.00 to t=1.65 seconds. Comparing the reconstructed image and the measurement results of the C-150 aircraft sound signal shows that the results are almost the same.

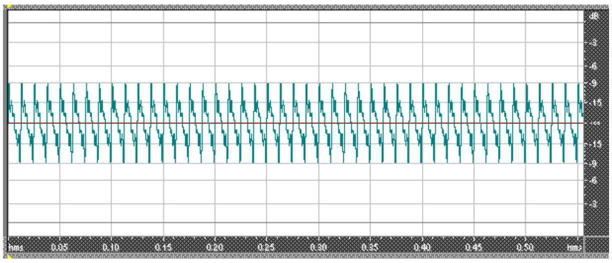

Fig. 8. Reconstruction of C-150 noise, taken at $t = 0.0\ s$ to $t = 1.65\ s$.

The data in Figure 6, which is then reconstructed in Figure 8, are data taken from a distance of 20 m with a height of 1.2 m. The data is taken from precisely the left of the propeller of the C-150 aircraft. The data is then processed using an FFT analyzer to obtain the response frequency. The results of the response frequency are shown in Figure 10. The data is then inverted to obtain the noise source. After the noise source signal is known, then the signal is processed to obtain an anti-noise signal that the multipole secondary source will issue. Lastly, Figure 10 and Figure 11, respectively, depicts the illustration of an anti-noise signal and the measurement of the anti-noise signal radiated by a multipole speaker system.

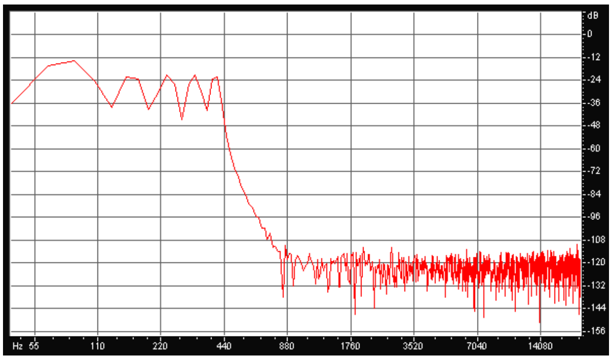

Fig. 9. Frequency response (FFT results) of the noise in Figure 8.

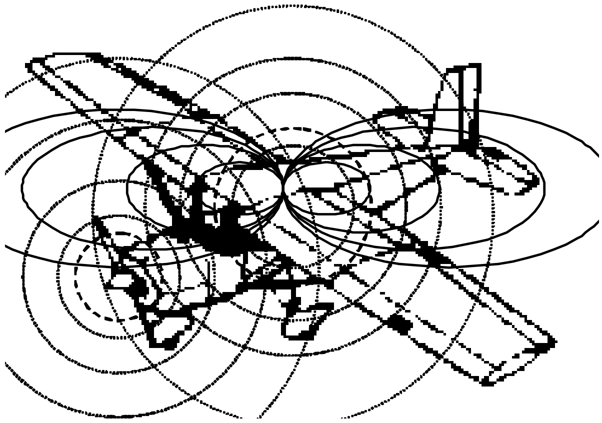

Fig. 10. Illustration of an anti-noise signal.

There will be a discrepancy between the calculation results and the implementation results. This is because there are several assumptions made when deriving the wave equation. When describing the concept of a multipole secondary source, it is assumed that the primary and secondary sources are located at one point, respectively. This cannot be done at the time of implementation.

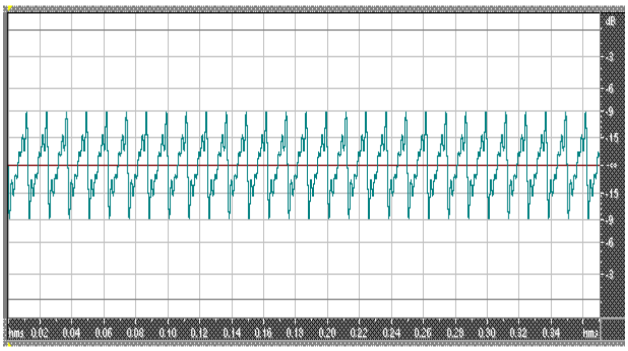

Fig. 11. Anti-noise signal radiated by a multipole speaker system.

VI. CONCLUSION

Free-field active noise reduction in aircraft using the multipole secondary source method is very promising, although the implementation still requires quite long research.

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