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INCE: 26.1.1

ACOUSTIC LOCATION AND SIZING OF IN DUCT OBSTRUCTIONS

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Introduction

This paper is concerned with applying acoustic impulse response analysis (IR) to the characterisation and location of finite obstacles present in a wave guide. The initial impetus for this project was in developing an IR technique to ascertain the condition of an in duct discontinuity with reference to its pressure loss in the presence of air flow. Further application is thus sought to spoiler air flow impedance characterisation. It was hoped that this may give rise to control or commissioning applications for HVAC installations. System impulse response is obtained using a Maximum Length Sequence System Analyser (MLSSA).

Research Background

A procedure for the sizing and location of in duct obstacles was developed by Qunli et al [1] from eigen frequency shifts for a given wave guide. While Qunli's theory appears to be complex and its applications perhaps slightly limited, the results give a remarkably accurate spatial representation of the obstacles present in the duct in any given plane.

Impulse Response Analysis reveals the distortion of an initial acoustic pulse in the time domain due to impedances, and capturing its subsequent distortions via windowing techniques, each distorted pulse may be frequency analysed using the Fast Fourier Transform (FFT). Comparison of the frequency response of an initial and a reflected pulse will give the frequency dependant reflection coefficient of the reflecting medium e.g. a spoiler. There is evidence to support an IR reflection coefficient analysis technique to ascertain the closed area ratio and the position of a plane in - duct spoiler in the transverse plane, but to gauge the longitudinal profile of a spoiler may present more difficulties. It is possible however that such information may be obtained from shifts in the reflection coefficient frequency curve due to changes in spoiler longitudinal profile. Such an approach may also lend itself to determination of pressure loss coefficient of a spoiler. If ratified, the latter approach could possibly be applied to the commissioning of ventilation systems, where pressure losses in the system must be balanced so as to achieve correct air flows and to minimise fan energy usage.

Research Approach

The prescribed procedure involves ascertaining the reflection coefficients, closed area ratios and pressure loss coefficients of spoilers situated in duct work configurations of various section, with views to establishing correlations. The duct work configurations consist of : a) 100 mm diameter plastic ducting of circular section, b) 150 mm square section thin gauge steel ducting. Of the above, b) was fitted with manometer tapping points for spoiler pressure loss determination, and connected to a low noise air handling unit which was very kindly designed, manufactured and supplied by Air Handling Equipment of Liverpool.

Initial tests used a source speaker mounted transversely inside duct a). In - duct obstacles used consisted of an angled spoiler positioned from 0 to 90 degrees to horizontal in 5 degree steps, and five diameters of orifice plate. Reflection coefficients are plotted against closed area ratio and existing pressure loss data.

For rig b) a side mounted speaker was used. Three sizes of strip spoiler are tested for reflection coefficients using IR, and also for pressure loss coefficient using pressure loss and air velocity measurements. However, the thin gauge duct work was of low mass and rigidity giving rise to break out and flanking transmission problems. Also the flange fittings etc. protruded inside the duct so reducing clarity of reflection measurement. A new precision made assembly of 2 mm gauge duct work has been acquired for further testing to try and reduce the above problems.

In each case the source signal was a pseudo random Maximum Length Sequence (MLS) signal provided by a DRA Maximum Length Sequence System Analyser (MLSSA). A problem with IR is in the reproduction of a short enough duration pulse to allow isolation of incident and reflected wave forms for windowing, with sufficient power to prevent background noise interference. A pseudo random signal has the same flat frequency response as an ideal impulse but can be reproduced more faithfully due to a smaller dynamic range, and also more powerfully, due to its longer period. MLSSA in effect cross correlates the initial signal and reproduced system distorted MLS signal in the time domain and thus converts the power contained in the sequence into an impulse response - peaks occur where the digital signal overlays a system distorted form of itself. The magnitude and definition of these peaks fluctuate inversely with the degree of signal distortion.

The cross correlation process in MLSSA is substantially simplified using the Fast Hadamard Transform algorithm (FHT). The digital MLS signal is in fact a train of 2 ^(17) -1 impulses randomly valued at positive or negative unity from a reference. The FHT in effect time shifts to zero (and proportionately to various time shifts where correlation occurs e.g. reflections) the system distorted train of impulses. As in cross correlation, this time shifting process concentrates the energy in one MLS period at time zero and proportionately at times of later reflection to give a powerful system impulse response. Due to the flat 0 dB frequency response of the initial digital signal, frequency analysis of the processed system IR at any time will give the system frequency transfer function of the acoustic path. The comparison of two pulses will give the transfer function due to the passage of the later pulse e.g. a reflection [2].

The distorted MLS signal was picked up at a microphone placed down stream of the speaker at a position designed to enhance pulse separation. Analysis was in the region of planar propagation below the duct cut on frequency. The band width of the source was set at 3 KHz, the cut on frequency being 2 KHz for the circular and 1100 Hz for the square duct. Above the cut -on frequency the pulse will begin to disperse as it propagates along the tube due to transverse components presenting a series of delayed distortions of the direct pulse and reducing impulse response definition. The source bandwidth includes non -planar frequencies but not enough to significantly effect the system impulse response.

Results

Figures 1-4 on the following page :

Fig. 1. shows one of the MLSSA processed impulse responses. Fig. 2. shows narrow band reflection coefficient frequency curve. Fig. 3. shows the reflection coefficient value at first maximum in the frequency curve - variation with closed area ratio. Fig. 4. shows the reflection coefficient as in Fig. 3. - variation with pressure loss coefficient **k**.

Conclusion

A clear impulse response similar to fig. 1. is required to accurately window and analyse each pulse component. From the position of each pulse in the time domain the location of a particular spoiler may be determined.

The first reflection coefficient (R.C.) maximum for plane orifice plates in fig. 2. occur at the cut on frequency of the duct (approximately 2000 Hz). This maximum value is employed in figs. 3 & 4. For angled spoilers the first maximum shifts away (and decreases in magnitude) from the cut on frequency as the spoiler moves away from the vertical. This frequency shift due to spoiler orientation suggests spoiler shape characterisation possibilities, and perhaps links with Qunli's eigen frequency work.

The effect of closed area ratio on reflection coefficient varies with angular orientation - the angled spoiler variation showing an exponential tendency as opposed to the plane orifice plate's more linear variation. This latter variation was also observed for the plane strip spoiler in duct rig b) suggesting a definitive correlation for spoilers in a fixed plane. Variations of R.C. with pressure loss coefficient showed a logarithmic nature as may be expected (fig. 4.). Results for both spoiler types in circular duct work point toward a universal correlation curve. The strip spoilers curve for b) had the same shape, but lower magnitudes of R.C. could perhaps be accredited to losses and inaccuracies previously cited.

Thus, these results indicate that the size and position of the first R.C. maximum in the discreet frequency curve may give insights into the size and shape of a particular duct work blockage, and also into its pressure loss characteristics.

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Acknowledgements

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Fig 1 : Impulse Response Time History For Angular Spoiler Set in 100 mm Diameter Circular Duct - Incident and Reflected Impulse Shown

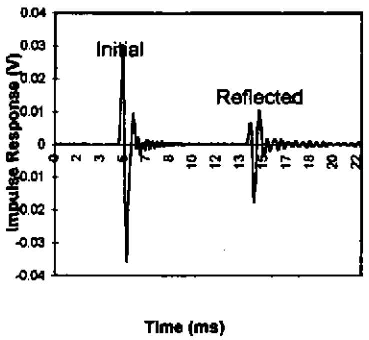


Fig. 2 : Variation With Frequency of Narrow Band Reflection Coefficient R For Angled Spoilers & Orifice Plates in a 0.1 m Diameter Duct

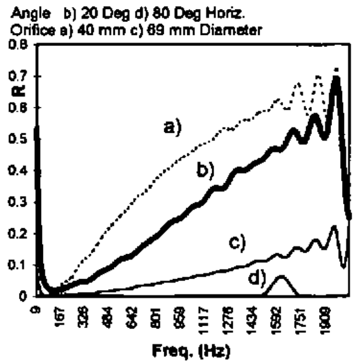


Fig. 3 Reflection Coefficient at First Maximum R Against Closed Area Ratio For Angled Spoilers And Orifice Plates In 0.1 m Diameter Duct

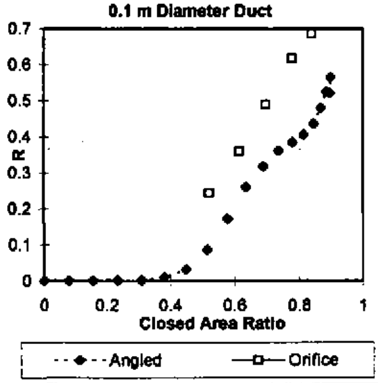
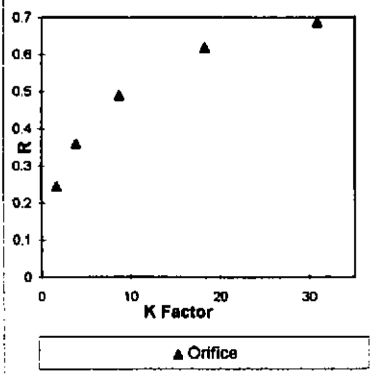


Fig. 4 - Reflection Coefficient at First Maximum R Against K Factor For Orifice Plates In A 0.1 m Diameter Duct



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INCE: 26.1.2

ACOUSTIC WAVE PROPAGATION IN A DUCT CONTAINING A SHEAR FLOW AND A LINE SOURCE

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INTRODUCTION

Ducted mechanical devices such as aircraft turbojet engines or air conditioning systems are major sources of noise. To attenuate this noise effectively, a thorough understanding of the acoustic properties of the system is required.

This paper deals with sound propagation in an infinitely long two-dimensional duct in the presence of an idealized mean flow. Of special concern is the influence of a thin shear layer with a linear velocity profile located at the upper duct wall. The present study is a first step in analysing the propagation of sound when there is an absorbent above the shear layer. The model discussed below, based on [1] and [2], is applicable to splitter silencers of both dissipative and reactive type found in ventilation and flue gas systems.

A solution of the present problem is found by analytical techniques, resulting in an inverse Fourier integral which is subsequently rewritten as an infinite sum of modes using residue calculus. In order to transform the integral into a sum, the duct modes have to be analysed. This is done with the powerful computer program *Mathematica* [3] and asymptotic analysis, yielding a complete modal analysis of the problem.

FORMULATION OF THE SHEAR FLOW PROBLEM

Consider acoustic waves in a two-dimensional duct, $-\infty < x < \infty$, $0 < y < b$, as shown in Fig. 1, with acoustically hard walls at $y = 0$ and $y = b$. A line source is located at $(0, y_0)$, where $0 < y_0 < a$. We consider the plane $y = 0$ to be a plane of symmetry so that only even solutions with respect to this plane are included. The flow velocity parallel to the x-axis is assumed to increase linearly in the shear layer and then remains at a constant value in the rest of the duct.

In order to derive a general wave equation, we neglect viscosity, gravity, thermal conduction and other dissipating processes as well as non-linear terms. By assuming a harmonic time dependence $\exp(-i\omega t)$ and adiabatic conditions, the following equation is derived [1] from the mass conservation equation and Euler's equation:

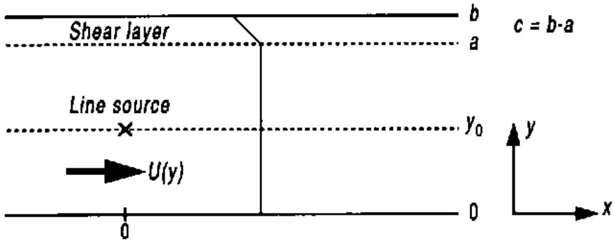

Fig. 1. The duct with a line source at $(0,y_0)$.

$$\left[U(y)\frac{\partial}{\partial x}-i\omega\right]^2\frac{p_0}{c_0^2\rho_0}p-\frac{p_0}{\rho_0}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)p-2U'(y)\frac{\partial v_y}{\partial x}=-\delta(x)\,\delta(y-y_0). \quad (1)$$

Here $U(y)$ is the flow speed, ω is the angular velocity, v_y is the particle velocity parallel to the y-axis and p_0 and ρ_0 are the constant ambient pressure and density, respectively. The constant speed of sound is denoted by c_0. In Eq. (1) the line source is represented by a two-dimensional Dirac's delta function. By convention, the right hand side of (1) is negative.

As boundary conditions we require the normal derivate of the pressure to vanish at the duct walls $y = 0$ and $y = b$. At $y = a$ the coupling conditions are given by continuity in pressure and particle velocity, and at $y = y_0$ the pressure is continuous but the particle velocity has a jump by -1 there. These last coupling conditions are obtained from Eq. (1) by repeated integration.

By using the Fourier transform

$$\hat{p}(u,y) = \int_{-\infty}^{\infty} p(x,y)\,e^{-ikux}dx,$$

where u is a non-dimensional axial wave number, and imposing the boundary and coupling conditions above, we find that the solution can be written as an inverse Fourier integral:

$$p(x,y) = \frac{k}{2\pi}\int_{-\infty}^{\infty}\frac{\varphi(u,y)}{\Lambda(u)}e^{ikux}du, \quad (2)$$

where $k = \omega/c_0$. Here φ and Λ are known analytic functions in u expressed in terms of confluent hypergeometric functions, which are implemented in *Mathematica*. We wish to rewrite (2) as an infinite sum of modes using residue calculus:

$$p(x,y) = \sum_n \pm ik\varphi(u_n^{\pm},y)\,\mathrm{Res}_{u=u_n^{\pm}}\left(\frac{1}{\Lambda(u)}\right)e^{iku_n^{\pm}x}, \quad (3)$$

where $u_n^{\pm}$ mean the zeros of $\Lambda(u)$ with positive/negative imaginary part. In case of a zero imaginary part, a small damping is introduced to get a finite imaginary part. In order to transform Eq. (2) to Eq. (3), the zeros of $\Lambda(u)$ must be investigated.

WAVE PROPAGATION MODES

We now study the zeros of $\Lambda(u)$ by using numerical procedures in *Mathematica* and asymptotic analysis. The modes have x-dependence $\exp(iku_n^{\pm}x)$, from which we see that when $u_n^{\pm}$ has a non-zero imaginary value, the modes are damped and non-propagating. For some value of the frequency parameter kb, corresponding to the cut-on frequency, $u_n^{\pm}$ become real and the modes start to propagate along the duct. The real part of $u_n^{\pm}$, denoted by $u_{n,re}^{\pm}$, is inversely proportional to the phase velocity by $v_{ph} = c_0/u_{n,re}^{\pm}$. For large $|u|$, an asymptotic analysis reveals that the zeros are divided into two series, one resulting from the shear layer and one coming from the uniform flow outside the shear layer. These two series are, asymptotically for large n,

$$u_{n,\,\mathrm{shear}}^{\pm} = \frac{2s\,(\sqrt{1-M^2}-1)+2i\pi\,(2n+1)}{s\,(M\sqrt{1-M^2}+\arcsin M)} \tag{4}$$

and

$$u_{n,\,\mathrm{uniform}}^{\pm} = \frac{-kaM+in\pi\sqrt{1-M^2}}{ka\,(1-M^2)}, \tag{5}$$

where $M = U(a)/c_0$ is the Mach number, assumed to be less than 1, and $s = kc/M$ is the Strouhal number, depending on the shear layer thickness c. Here n is any large integer. It is satisfactory to note that Eq. (5) gives the same result as that obtained in a duct of width a without a shear layer.

By using the secant method, which is a built-in procedure in *Mathematica*, the zeros of $\Lambda(u)$ are calculated numerically. For $M = 0.1$, $c/b = 0.01$ and kb small (say $kb = 0.01848$), the first nine zeros are

$u_0^+ = 235.394,$

$u_1^- = -1.11043,$

$u_1^+ = 0.90947,$

$u_2^{\pm} = -26.1648 \pm 160.115i,$

$u_3^{\pm} = -39.1675 \pm 276.275i,$

$u_4^{\pm} = -16.2603 \pm 431.566i.$

By using asymptotic analysis in the two limits $k \to 0$ and $k \to \infty$, we conclude that u_0^+ corresponds to a hydrodynamic mode, u_1^- and u_1^+ to plane acoustic modes and $u_n^{\pm}$, $n > 1$, to higher acoustic modes.

If we require all modes to be causal [2], we find that the hydrodynamic mode u_0^+ propagates downstream with a fairly low phase velocity and that the plane modes u_1^- and u_1^+ propagate upstream and downstream, respectively, the latter having a larger phase velocity due to the mean flow Mc_0. In Fig. 2 below we show schematically the behaviour of the modes in the complex u-plane when kb varies from 0 to ∞. Here we see that when a higher acoustic mode becomes real, it continues to the right or to the left along the real axis and approaches u_1^- or u_1^+, depending on whether it is a minus or plus mode. Also, an asymptotic analysis shows that $u_0^+ \to 1/M$ as $k \to \infty$, M being small.

Finally, by using results from [4], we conclude that all modes, acoustic and hydro-

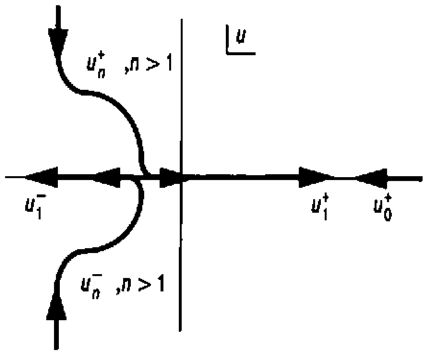

Fig. 2. Behaviour of $u_n^{\pm}$ as kb, real, varies from 0 to ∞.

dynamic, are stable for all frequencies. For an example of an unstable hydrodynamic mode, see [2], where a vortex sheet is analysed.

CONCLUSIONS AND FUTURE RESEARCH

By using analytical techniques, the sheared flow duct problem has been solved. *Mathematica* has been proven to be a powerful tool in analysing the modes. Our main results include the study of the hydrodynamic mode and the discovery of two different series of acoustic modes.

Future research will concentrate on a duct with a shear layer next to an absorbent described by an equivalent fluid model. In this duct we expect to find two hydrodynamic modes of which one is unstable for Strouhal numbers below some critical value. The shear layer is important to include in silencer calculations for two reasons.First it is required in order to model the attenuation properly, particularly at high frequencies. Secondly, the hydrodynamic modes that are introduced via the shear layer are imperative for describing the modal conversion in the beginning and end of a silencer via the so called edge condition.

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IDENTIFICATION AND ANALYSIS OF NOISE PROPAGATED BY DUCTS

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In practice frequently it is necessary to identify noise propagated by ducts. As an initial value it is desirable to select such which could be easily measured or data on the mean values of which could be available. The normal (radial) velocity of vibrations of duct walls may serve as such value.

In the work [1] it was shown that noise outside ducts may be created by a zero wave that propagates inside the medium. This wave forms a sound field outside, sound pressure in which p (r, z) may be written in the form:

$$p(r,z) = p_0 e^{i\gamma z} H_0^{(1)}(\mu r). \tag{1}$$

Here $H_1^{(1)}$ - Hankel function of the firs order 0; γ and μ - components of wave vector $k=\omega/c$ along the axis of the ducts z and r, accordingly; c - sound velocity in the air; p_0 - constant amplitude. For simplicity of recording, temporal multiplier $e^{-i\omega t}$ in the formula (1) is omitted.

Radial vibration velocity V (r, z) is linked with sound pressure p (r, z) by the relation

$$V(r,z) = \frac{1}{i\rho\omega}\frac{\partial p(r,z)}{\partial r} = -\frac{\mu_0}{i\rho\omega} p_0 e^{i\gamma z} H_1^{(1)}(\mu,r), \tag{2}$$

where $H_1^{(1)}(\mu r)$ - Hankel function of the firs order I; ρ - air density.

If the radial velocity of duct walls is taken in the form $V(z) = Ve^{i\gamma z}$, then at $r = aV(a,z) = Ve^{i\gamma z}$ where from

$$p_0 = -\frac{i\rho\omega}{\mu}\frac{V}{H_1^{(1)}(\mu a)}, \tag{3}$$

where a duct radius.

Having inserted expression (3) into equality (1), we shall get the relation between pressure at some point (r, z) with the radial velocity of vibration of duct walls V:

$$p(r,z) = -\frac{i\rho\omega V}{\mu}\frac{H_0^{(1)}(\mu,r)}{H_1^{(1)}(\mu a)}e^{i\gamma z}. \tag{4}$$

Expression (4) is true for ducts of infinite extension or for ducts of finite length L, which is considerably larger than r - the distance from the point under observation to the axis. However, in practice, cases frequently occur when the final area of the ducts of the length L and r>>L radiates the sound. Then the sound field will already be not cylindrical, but spherical. An issue comes forth what way it is possible to assess sound pressure in that case.

This can be done in the following way: to define the sound power P, which is radiated by the duct section of length L, and then to use the known pressure $L_P=10\ \lg\ [P\phi/(P_0S)]$, where ϕ - directivity factor; $P_0=10^{-12}$ W; S - spherical surface area, surrounding the space, in which sound radiation occurs. If radiation takes place into the open space, then $S=4\pi R^2$, where R - distance (m) from the point under observation to the acoustic centre of the source, which for the duct lies on the axis in the middle of its length. If the duct radiates sound into the semispace, then $S=2\pi R^2$.

The power of the radiated sound P for the duct of length L may be defined, after calculating P_0 - power, radiated to the unit of duct length: $P_0=2\pi rq$, where q - sound intensity, radiated by the pipeline at radial direction.

According to [2]

$$q = \frac{|P_0|^2}{\pi\rho\omega r} \tag{5}$$

where from

$$P_0 = \frac{2|p_0|^2}{\rho\omega}.$$

Having inserted into equality (5) the value $|p_0|^2$ from the equality (3) we shall get

$$P_0 = \frac{2\omega\rho|V|^2}{\mu^2|H_1^{(1)}(\mu a)|}. \tag{6}$$

For defining of full power P, the duct should be split into sections, within the boundaries of which the velocity of wall vibrations V may be considered approximately the same, to calculate the power radiated from j-th section of length L_j and to sum up P_j along the whole line: $P = \sum_L P_j$.

Thus, at a distance R from the middle of the duct of length L up to the point of observation, which is significantly larger than L, the level of sound pressure may be evaluated by formula:

$$L_P = 10\lg\left[\frac{\Phi}{P_0 S}\sum_L P_j\right] = 10\lg\left[\frac{2\omega\rho\Phi}{P_0 S\mu\left|H_1^{(1)}(\mu a)\right|^2}\sum_L P_j\right]. \qquad (7)$$

Values μ for a zero wave are provided in the work [3]. At a broad range of frequencies (with the exception of the lowest).

$$\mu \approx k\sqrt{1-\frac{c_1^2}{c_2^2}},$$

where c_1 - sound velocity in the medium, running along the duct.

Value $\left|H_1^{(1)}(\mu a)\right|^2 = C_1^2(\mu a)$ may by defined according to the tables [4]. At high frequencies when

$$\mu a = ka\sqrt{1-\frac{c_1^2}{c_2^2}} \rangle 1, \quad \left|H_1^{(1)}(\mu a)\right|^2 \approx \frac{2}{\pi\mu a} = \frac{0{,}6366}{\mu a}.$$

On calculating the levels of sound pressure according to formula (7) the influence of the earth should be taken into account, since the wire is usually located horizontally at a distance d (m) of the axis from the earth. It is possible to take into account the influence of the earth, taking the surface ρ equal not to $4\pi R^2$ but to $2\pi R^2$. Then L_{P_1} increases by 3 dB as compared with the duct radiation without taking into consideration the effect of the earth L_{P_0}.

At the same time the coefficient of sound reflection from the earth is close to 1. Therefore the earth in the first approximation may be considered absolutely rigid and at the calculations of sound pressure the method of imaginary source be used. For the purpose of satisfying the conditions on the surface of the earth (normal speed equals 0), it is necessary to take a minimum source of the same sign as the duct (mirror reflection as regards the earth - Fig. 1). At great distances of the point under observation from the wire rays R, R_0 and R' run almost in parallel and the difference of the motion $k\Delta = kdsoc\Theta$ (Fig. 2), where Θ - is the angle between the normal to the earth and the direction to the point under observation.

For angles $\pi/2 \geq \Theta \geq \Theta_0$ at which $kd\cos\Theta_0 << 1$, pressure from the real and imaginary sources gets constituted cophasally and, correspondingly, pressure becomes doubled, i.e., L_{P_1} exceeds by 6 dB. It is true for all objects that are located at distances $H = R_0\cos\Theta_0$ from the earth. Since the earth is not absolutely reflecting the surfaces, then L_{P_2} differs from L_{P_0} less than by 6 dB. The real result, evidently, is placed between L_{P_1} and L_{P_2}.

Conclusions

1. Formulae obtained make it possible to establish the relation betseen the radial speed and sound pressure of duct wall oscillations of infinite and finite length.
2. Having used this relation, the radiated power by duct walls was defined.
3. According to formulae of the power radiated by the duct walls, it is possible by a known method to find the sound pressure level at a desirable point.
4. On evaluating the level of noise of the duct at great distances R, it is necessary also to take into account the sound attenuation at its propagation along the earth surface.
5. For the extensive ducts, the sound field of which is close to the cylindrical one, it is possible to use the same formulae, which are used on evaluating the level of sound pressure of transport flows.
6. At a not great length of duct L (spherical sound field at great R) it is possible to use formulae which are applied at calculating the level of sound pressure on the building and industrial territories.

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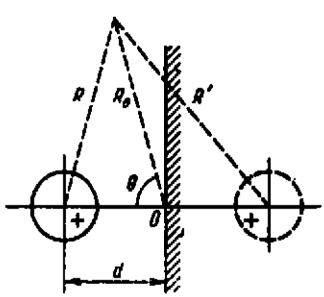

Fig. 1. A scheme of mirror reflection as regards the earth

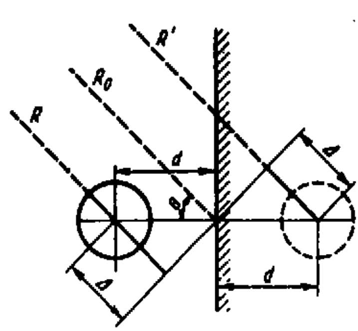

Fig. 2. A scheme of calculating of the field of two jointly operating monopolies at the far zone