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PNEUMATIC SOUND GENERATOR WITH FREQUENCY-INDEPENDENT CONTROL OF DIRECTIVITY CHARACTERISTIC

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1. Introduction

For most ANC application directed sound generation is of great theoretical importance, but in reality no directed sound generator exists. Conventional sound generators use the mechanism of volume displacement, they work only as acoustical monopole source and have a spherical directivity characteristic. Only with large arrays of monopoles sound direction at middle an low frequencies is achieved. Following a sound generator is presented that works not only as a monopole source but also as a strong dipole source. Superposition (tripole, **Fig.1**) leads to directed sound generation with "cardioid" characteristic in free space or "unidirectional" characteristic in the one-dimensional case (without large arrays of monopole sources or wide dimensions of the sound generator).

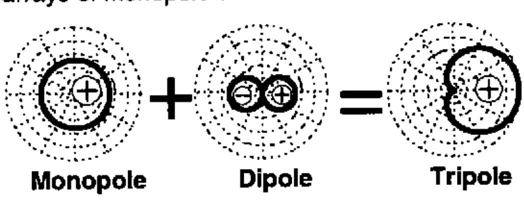


Fig. 1
Acoustical Tripole
Superposition of monopole and dipole source results in an acoustical tripole.

2. Theory

For realization of a monopole source together with a strong dipole source a modulated high speed air jet (velocity c_F) is ejected through a nozzle. The modulated jet causes sound by volume displacement of the ambient air. Additionally the modulated jet transfers a timevariant force to the ambient medium that causes dipole radiation (**Fig. 1**).

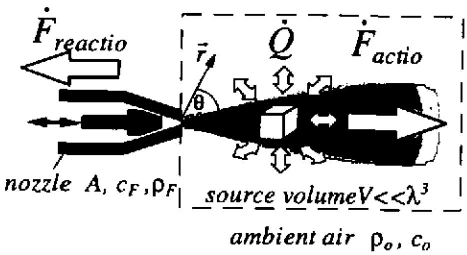


Fig. 1
Directed Sound Generation
A fluid mass flow is ejected by a nozzle with opening A. The ejected jet causes monopole radiation by volume displacement Q and dipole radiation by impulse transfer (force F) on to the ambient air.

The sound field of the modulated jet is governed by the inhomogeneous wave equation [1]

$$\left(\nabla^2 - \frac{1}{c_o^2}\frac{\partial^2}{\partial t^2}\right) p(\vec{r},t) = -\underbrace{\rho_o\, \dot{q}(\vec{r},t)}_{Monopole} + \underbrace{\nabla\cdot\vec{f}(\vec{r},t)}_{Dipole} - \underbrace{\nabla\cdot T(\vec{r},t)\cdot\nabla}_{Quadrupole}$$

$q(x,t)$ [m³/s/m³=1/s] is the net volume source strength per cubic meter and $f(x,t)$ [N/m³] is the net force per cubic meter acting on the control volume. Following the quadrupole term $\nabla\cdot T(\vec{x},t)\cdot\nabla$ will be neglected, because its radiated power is small compared to the power radiated by monopole and dipole. For a compact source region, being small in comparison to the sound wavelength, the solution of the equation can be derived:

$$p(\vec{r},t) \quad = \quad -\frac{\rho_o\ \dot{Q}(t-r/c_o)}{4\pi\, r} + \frac{\nabla\cdot\vec{F}(t-r/c_o)}{4\pi\, r} \qquad (V \ll \lambda^3)$$

With a constant fluid velocity c_F the divergence of the force F is given by

$$\nabla\cdot\vec{F}(t-r/c_o) = \nabla\cdot\left(\dot{m}_F\ \vec{c}_F\right) = \cdot\left(\rho_F\ Q(t-r/c_o)\ \vec{c}_F\right) = -\rho_o\,\dot{Q}(t-r/c_o)\ \frac{\rho_F\,\vec{c}_F}{\rho_o\,c_o}\ \frac{\vec{r}}{r}$$

After ejection thermodynamic processes between ambient air and fluid (heat transfer, combustion, condensation, vaporization) take influence on the monopole, if they occur fast in comparison to the modulation period. A variation of the specific enthalpy of the ejected fluid Δh_F after ejection causes an additional change of volume flow $\dot{Q}_{th}$ ($c_{p,o}$:specific ambient heatcapacity)

$$\dot{Q}_{th}(t) = -\frac{\dot{m}_F(t)\,\Delta h_F}{c_{p,o}\ \rho_o\ T_o}$$

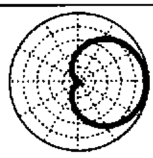
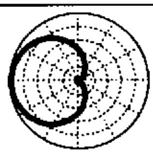
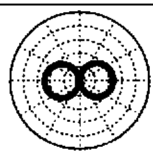
The volume flow depends on the ambient thermodynamic state. With the **m**onopole factor R_M and **d**ipole factor R_D

$$R_M = 1 + \frac{\dot{Q}_{th}}{\dot{Q}} \qquad\qquad R_D = \frac{\rho_F\ c_F}{\rho_o\ c_o}$$

leads to the total sound pressure in free space

$$p(\bar{r},t) = -\frac{\rho_o \dot{Q}(t - r / c_o)}{4\pi r}\left(R_M + R_D \cos(\theta)\right)$$

The relationship between the factors R_M und R_D determines the resulting directivity characteristic. Conventional sound generators act with $R_M >> R_D$. If the air is ejected with velocity c_F equal to sound velocity, i.e. $R_M = R_D = 1$ in free field cardioid directivity characteristic, in a duct uni-directional directivity characteristic can be achieved.

	R_M, R_D	Volume flow Force	Directivity haracteristic
Ideal Gas **Humid air** **Vapor** **Liquids/ Solids** - isochore change of state - heat transfer from fluid to air	$R_M = R_D$	$Q_{res} > 0$ F	
(Hot) Water - in dry air (evaporation) **Liquids/ Solids** - isochore change of state - heat transfer from air to fluid	$R_M = -R_D$	$Q_{res} < 0$ F	
(Cold) Water - in saturated air - no evaporation **Liquids/ Solids** - isochore change of state - no heat transfer	$R_M << R_D$	$Q_{res} \approx 0$ F	

Tab. 1 Influence of the injection medium directivity characteristic

3. Measurement Results

For ejection of the air a nozzle (Ø 5mm) is used, that periodically modulates a fluid flow ($c_F = c_o$ respectively $R_M = R_D = 1$) with an inner rotor like a siren. The fundamental frequency is 100 Hz. The measured directivity characteristic (normalized!) of the first five harmonics of the sound pressure spectrum in free space is depicted **(Fig. 2)**. The expected cardioid characteristic is obvious. For measurements in a duct the nozzle is lengthened by a flexible small tube of a length of 100 mm and an inner diameter of 4 mm. The tube is fit in a long duct of 4 m and a inner diameter of 50 mm and directed on the middle axis of the duct. In front and behind the tube are 2m duct, which are terminated with absorbers wedges (border frequency of 100 Hz) to avoid reflections. The spectrum of the sound pressure level is shown in **Fig. 3** The frequency independent, nearly unidirectional radiation is proved (level difference in / against the jet direction:15 to 25 dB).

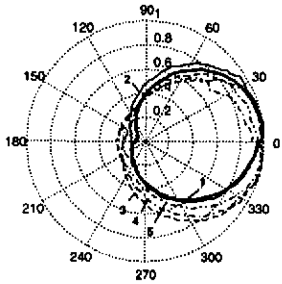


Fig. 2 Directivity characteristic in free space, 1. (100 Hz) to 5. (500 Hz) harmonic

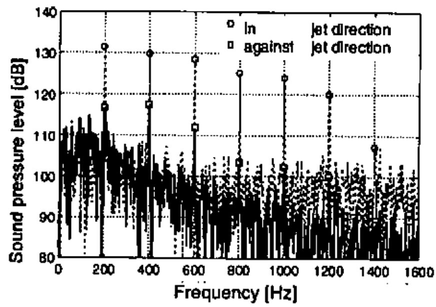


Fig. 3 Spectrum of the nozzle (Ø 4 mm) ejecting in a duct of 50 mm diameter measured in / against the jet direction

4. Applications

Because of its unique directivity characteristic the sound generator can act as directed siren for ambulance cars etc. It also can be used for the purpose of active noise control. In ANC systems the directivity allows cancellation without reflecting of incoming waves. The main application will be active noise cancellation of exhaust noise, because in a duct of small cross section area high sound pressure level can be realized. Besides this the sound generator is small, light and robust (**Fig. 4**).

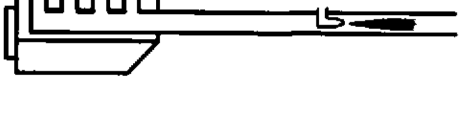


Fig. 4
Active Exhaust Noise Cancellation
The sound generator ejects into the exhaust duct.

References

[1] Morse, P. M., Ingard, K. U., Theoretical Acoustics, McGraw- Hill, Princeton, 1968