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ACTIVE NOISE CANCELLATION : A FEASABILITY STUDY

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1. INTRODUCTION

Active noise cancellation, using anti-sources which are properly dephased with respect to the original noise source, is a relatively new and promising noise reduction technique. Much has been published on the theoretical background of the method, but little is known about real life applications.

The topic of this paper is a feasability study, using an experimental approach. Some of the principles of active noise cancellation will be highlighted, using simple point source configurations in combination with a simplified acoustical radiation model.

The major part of the paper deals with the application of active noise cancellation principle on plate-like structures, in ducts and as an alternative earprotection, using headphones. The noise cancellation efficiency has been studied on loudspeaker configurations.

2. PRINCIPLES OF ACTIVE NOISE CANCELLATION

2.1. Acoustical interaction in a dipole configuration.

It is a well known phenomenon that two or more sound sources, when put together will interfere, creating zones of amplification and zones of extinction. If the sources are close together, they will not only interfere, but also interact, yielding a decrease of the total radiated sound power. Such phenomenon is often referred to as an acoustical short circuit. A mathematical approach to caracterise this loss of radiated power is only possible for point source configurations, with a finite strength and infinite dimensions.

Consider for example a dipole, which is the superposition of two point sources as illustrated in figure 1. The caracteristics of this configuration are :

- $2h$: the separating distance between both monopoles
- β : the phasedifference between the monopoles
- Q_1 and Q_2 : The source strengths
- ω : the pulsation of the vibration
- k : the wavenumber , $k = 2\pi / \lambda$

The dipole configuration generates a soundpressure- and particle velocity field, which is the superposition of the fields from both individual sources. After integration of the normal component of the real part of the acoustic intensity over a sphere around the dipole, the total radiated power can be calculated :

$$W_T = \frac{Q_{1rms}^2 \, k^2 \, Z_o}{4\pi} \left(1 + Q_o^2 + 2\, Q_o \frac{\sin 2kh}{2kh} \cos\beta \right) \quad \text{with } Q_o = \frac{Q_{1rms}}{Q_{2rms}} \qquad (1)$$

If one compares the dipole power to the power radiated by a single point source of strength Q one gets the following ratio :

$$W_T / W = 1 + Q_o^2 + 2\,Q_o \frac{\sin 2\,k\,h}{2\,k\,h} \cos \beta \qquad (2)$$

This power ratio is function of the product of the wavenumber k and the separating distance h, and theoretically the power radiated by two identical point sources can be reduced to zero if they are 180° out of phase. Although point sources do not exist in reality, one can derive useful conclusions for real life applications from this point source representation.

2.2. Simulation of active sound cancellation using a radiation model.

To evaluate the applicability and the limits of active noise cancellation methods on more complex source configurations, one can use numerical radiation models. Such models which predict the sound field for given boundary conditions do exist in a wide variety. Within the framewall of this study a model based on the Helmholtzintegral (ref. 1) has been applied to analyse the potentials of the cancellation technique in reducing the noise generated by vibrating structures (structure-born noise).

In a first example the radiation model is used to calculate the acoustic intensity pattern generated by a dipole configuration. At a separation distance between the two sources of 10 cm and a frequency of 200 Hz, the optimal source strength ratio is given by Q_o = 0.91. The pronounced short circuit can be clearly observed in the calculated intensity patterns (fig. 2). The real intensity shows the energy flux from the source to the sink, while the ratio between imaginary and real intensity is an indicator for the reactivity of the near field. There is only a marginally small acoustic energyflux escaping from the center of the configuration. The total sound power reduction is 8 dB, with respect to the power radiated by a single source.

A more realistic example of these simulation techniques is given in figure 3. The velocity patterns of an aluminum plate (535x340x13 mm) measured for a resonance frequency (first bending mode) has been used as input for the radiation model. The resulting intensity pattern parallel to the plate gives an indication about the optimal position of the anti-sources. These anti-sources can be simulated by adding additional sources with appropriate phasing to the original vibrating surface. The total reduction in radiated power which could be observed by adding one anti-source is, according to this simulation 15 dB. Those and other results confirmed that the cancellation principle is valid for structure born noise, and justifies that its success will depend on the implementation efficiency.

In a future phase the radiation model will be a integrated in an optimalisation technique for active noise cancellation, by using the model in an iterative way, changing the functional parameters to obtain a maximum noise reduction.

3. FEASABILITY STUDY ON LOUDSPEAKERS

To confirm the findings of the simulation analysis and to gain more practical experience with and insight in the noise cancellation, it was decided to apply the technique first to loudspeaker configurations. Loudspeakers have the advantage that their output is well defined and easy to control, which makes them easy sources to experiment with.

The principle of the feasability study was to consider one loudspeaker as being the original source and to reduce its radiated sound power with one or more loudspeakers as anti-sources.

Two loudspeaker configurations (side by side, face to face) have been compared. As expected, the face to face configuration was the most efficient. By driving the loudspeakers with a sine wave, a clear cancellation at the basic frequency was yielded (25 dB at an optimal phase shift of 180°). At higher order harmonics which were caused by unavoidable loudspeaker distortions, an amplification could be observed, since for those frequencies the ratio separation distance to wavelength was too high. This fact can not be neglected when selecting anti-source loudspeakers.

One has to realise that, when using the face to face configuration, a part of the reduction of the radiated sound is due to passive absorption, caused by the presence of the second loudspeaker in the radiation field of the primary source. By measurements it was shown that at 400 Hz (the optimal frequency for a separation distance of 0.06 m) the passive absorption amounts 3.4 dB and the active attenuation 20 dB.

To visualize the cancellation mechanism, the nearfield intensity pattern of the loudspeakers has been measured, using a 3-D intensity measurement probe mounted on a positioning robot (ref. 3). Some typical real intensity patterns for loudspeaker configurations are represented in figure 4. These patterns indicate why the noise cancellation for the side by side configuration is less effective; the two extremities of the loudspeakers do not influence eachother, and radiate to the far field. In the face to face configuration this is much less pronounced.

The tests on loudspeaker configurations illustrate the feasability of the active noise cancellation technique. For a maximal noise cancellation the following can be stated :

- the separation distance between source and anti-source has to be minimal
- the escaping sound energy flux must be minimalised, face to face or ring configurations yield better results than side by side
- the cancellation is more effective at lower frequencies
- the source strength ratio is function of frequency and configuration
- the phase-shift between sources has to be 180 °

4. ACTIVE NOISE CANCELLATION ON PLATELIKE STRUCTURES

When applying the active cancellation technique to structure born noise the following problems need to be solved : what signal should be used to feed the anti-source, how should it be conditioned, what should be the dimension, the position and the strength of the anti-source. Since structure born noise is often generated by platelike structures, it was decided to limit the feasability study in this initial stage to plates, with the use of loudspeakers as anti-sources.

The anti-source must be driven with a signal, opposite to the sound generated by the plate vibrations. It is therefore necessary to monitor the sound or the structural vibrations close to the position of the anti-source, and use this signal after conditioning as input for the anti-source. However, using the sound pressure as input signal is precarious since a closed loop is created (loudpeaker - microphone - loudspeaker) which becomes easily unstable. It was therefore decided to use the plate velocity, as input for the anti-source. Hereby one assumes that the vibrating behaviour of the plate is not influenced by the pressure generated by the anti-source.

The number of anti-sources and their optimal position is function of the structural vibration pattern. The anti-sources will have an optimal effect on the noise radiation in areas with a maximal sound energy flux to the far field, where the largest real intensities are measured.

As expected the cancellation using one loudspeaker as anti-source was the most effective for the first resonance frequency which corresponds to the first bending mode. This mode is at the same time characterised by a relatively high radiation efficiency and a fairly simple deformation pattern, so that a considerable sound power reduction could be obtained by positioning one loudspeaker above the center of the plate where the largest energy flux occurs.

With the use of 3-D intensity measurements a qualitative view on the active noise cancellation was obtained (fig. 5). The real flux from the loudspeaker to the plate shows the acoustical short circuit between both, which is confirmed by the imaginary pattern (ref. 8). It is however remarkable that the radiation from the side-flaps of the plate is increasing when the anti-source is driven. The artificial short circuit disturbs the normal, natural short circuits. When measuring the radiated sound power and comparing it with the initial power, the following values are obtained :

	init. P	after canc.	P
basic frequency : 238 Hz	85.4 dB	76.0 dB	- 9.4 dB
first harmonic : 476 Hz	62.5 dB	72.8 dB	+ 10.3 dB
second harmonic : 714 Hz	48.9 dB	54.7 dB	- 5.8 dB

As for the two loudspeaker configurations, the loudspeaker acting as anti-source generates higher order harmonics, yielding at those frequencies an increase in sound power. It is therefore essential that one uses only high quality loudspeakers with a low harmonic to fundamental ratio as anti-source.

With the same configuration the reduction of radiated sound power was not so spectacular for the second, double bending mode of the Al-plate, with only 4.6 dB reduction on the basic frequency of 629 Hz. This modest result is due to the complexity of the vibrating mode, and the need for more than one loudspeaker to efficiently cancel out the radiated power, which is the subject of our current research.

5. ATTENUATION OF NOISE IN A VENTILATION DUCT

An analytical evaluation of active noise cancellation in ducts is rather cumbersome, due to the unknown impedances up- and downstream the anti-source(s). Therefore the experimental approach seems appropriate. All tests are performed on a wooden, rectangular duct (0.15 x 0.15 m; 3 m length).

For the first configurations the original source used is a simple loudspeaker. This offers the possibility of evaluating the desired filter caracteristic between the original source and the control signal of the anti-source. One would expect thios caracteristic to be a pure time-delay for all frequencies. This is confirmed by the transfert function measured between the sound pressure at the primary source and at the anti-source (anti-source non active).(fig. 6)

Momentaneously the phase shift and amplification are controlled manually, but an automatic, computer controlled system, based on a pure time-delayer will be available in the near future. This will enable adaptive control, minimising the sound pressure at the end of the duct. The system could also be the basis for a digital programmable filter.

A first series of experiments was conducted using the same signal to control the primary and secondary source (with a proper amplification and phase shift for the latter). For this configuration a reduction in radiated sound up to 17 dB was be measured at the end of the duct for all frequencies from 100 to 1000 Hz. To analyse the cancellation mechanism acoustic intensity measurements were performed inside the duct, along its length axis. The resulting diagram is plotted in figure 7, and shows clearly the cancellation. At the position of the secondary source the reduction in sound energy flux (represented by the real intensity pattern) is remarkable. Since the evaluated frequency is far below the cut-off frequency of the duct, only axial sound power flow is present. The qualitative evolution of real and imaginary part of the intensity in the duct confirms the theoretical derivations found in litterarture (ref.4).

In a second series of experiments a microphone has been used to control the anti-source. The microphone was positionned close to the primary source. The major problem in this configuration was the occurance of instabilities. The system microphone - filter - secondary source yields a closed loop, making the whole configuration unstable. This problem can be solved using loop-stabilising filters. Another approach is the acoustical separation of the detection microphone and the anti-source. This was applied with a directional microphone in combination with a directional anti-source. The first is commonly available on the market, while the directional source was realised using two loudspeakers with a proper dephasement (fig. 8). An attenuation of 15 dB was obtained for most frequencies between 100 and 1000 Hz.

During a third experiment a ventilator was used as primary source. The spectra before and after cancellation are shown in figure 9. No instabilities occured.

6. ACTIVE NOISE CANCELLATION AT THE EAR

Unlike both previous cases (cancellation in ducts and on plates), the active noise cancellation at the human ear does not attenuate the radiated sound power, but is only reducing the sound pressure locally (at the ear) based on interference between the original sound waves and the anti-source signal. In order to yield local interference patterns at the ear, the anti-sources must be positionned as close as possible to the ear. Conventional headphones fulfill this condition. The anti-sources are driven by properly conditionned microphone signals originating from two additional microphones mounted as close as possible to the headphone loudspeakers.

This basic principle implies an uniform phase-shift as necessary filter caracteristic between the original noise at the ear and the anti-source signal. This is confirmed by measurements, as is illustrated in figure 10, where the transfert function between microphone and loudspeaker is given.

For single-frequency noise the measuered influence of phase-shift and anti-source strength is shown in fig. 11. It is interesting to remark the phase-shift of 180 ° for optimal cancellation. Both phase-shift and amplification are rather critical, but are stable over a large frequency range.

A phase-shift of 180 ° can be easily obtained for all frequencies by a simple reverse of polarity in the electrical circuit. Such a system is off course the most simple and the less expensive. With the use of a cheep, open type headphone and plain electret microphones a very light, pleasant and economic system is build. The performance for white noise is shown in figure 12. The poor performance below 400 Hz is due to an additional phase-shift caused by the headphone loudspeakers. This will probably improve with loudspeakers of a higher performance. The distance between source and observer as well as the orientation of the head showed very little influence.

With optimal signalconditioning the performance on single frequency noise is certainly better (fig.13).

Compared to other personal ear protection techniques this system has the advantage that the earphones are light and that it allows the superposition of music or communication signals on top of the anti-source signal. Digital signal processing will undoubtly allow higher performance since it enables various filter caracteristics, but for applications on headphones such a system is to our opinion too complex and expensive.

7. CONCLUSIONS

Based on theoretical considerations on point sources and on the simulation with a numerical radiation model the validity of the cancellation technique was proven. The optimal phase-shift and separation distance as well as the amount of cancelled sound power were experimentally confirmed using loudspeakers.

Active noise cancellation on real-life platelike structures has more limitations and requires a combined use of several anti-sources.

The major problem when applying the active noise cancellation in ducts is the instability of the system. This instability can be reduced when using directional microphones and sources. Such a system yielded good results, with attenuations up to 17 dB for single frequencies. A pure time-delay filter will allow broad-band attenuation.

Another succesfull application of the active cancellation technique was the realisation of an effective, economical personal earprotection system, using light, open headphones and simple electret microphones.

For all applications the attenuation can be improved using digital filters. When these are programmable, adaptive systems will yield even better results.

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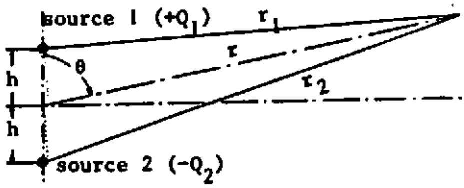

fig. 1 dipole configuration

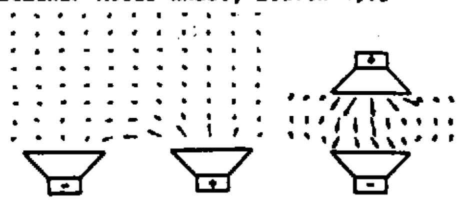
fig. 4 measured real intensities for loudspeakerconfigurations

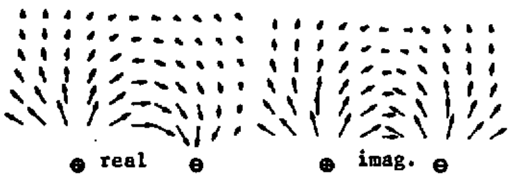

fig. 2 intensity patterns for a dipole

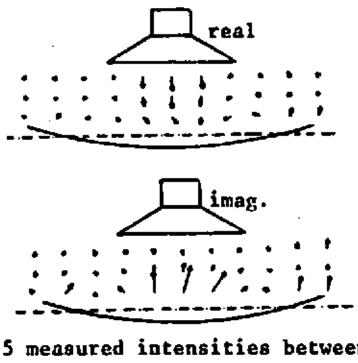

fig. 5 measured intensities between plate and loudspeaker

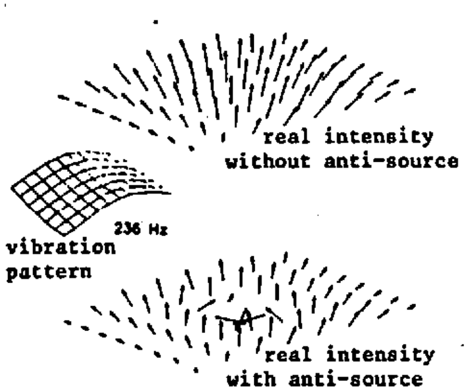

fig. 3 simulated patterns above Al-plate

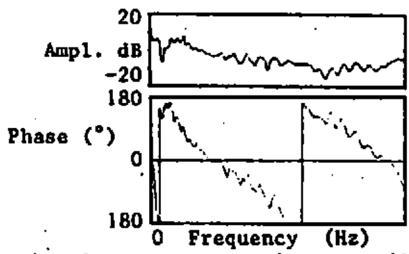

fig. 6 control of anti-source (duct)

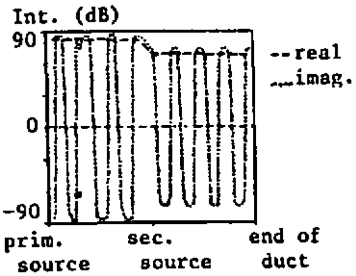

fig. 7 Intensities in duct

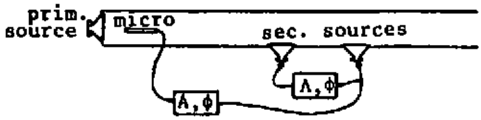

fig. 8 test set-up for cancellation in a duct with directional anti-source

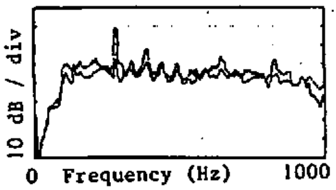

fig. 9 cancellation of ventilator-noise in duct

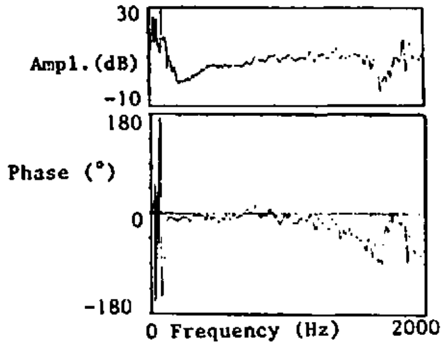

fig. 10 control of anti-duct (headphones)

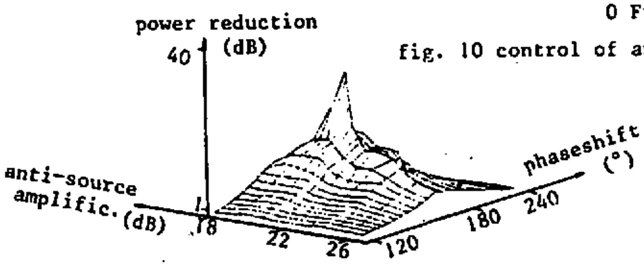

fig. 11 cancellation using headphones at one single frequency

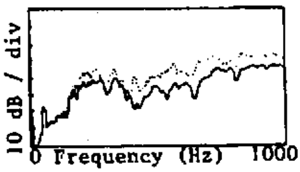

fig. 12 cancellation with headphones on white noise

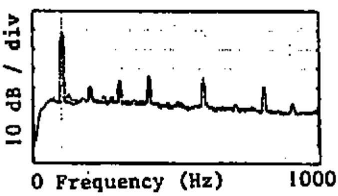

fig. 12 cancellation with headphones on spectrum with one dominant freq.