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NOISE REDUCTION IN ROOMS USING ACTIVE AND PASSIVE CONTROL ON THE BASIS OF MODAL ANALYSIS

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Abstract. *Some of advantages and disadvantages of active and passive noise control in rooms at low frequencies are considered in this paper. Examples described in the paper stand for the modal analysis of sound field being used to reduce SPL in some areas of the room employing secondary sound source - active control, as well as the analysis of SPL reduction in the same room having absorbing ceiling - passive control. The main purpose of this paper is to give information about some practical applications of active and passive control of sound field in a room, and to show advantages of detailed modal analysis that can be done using computer software. Computers are now powerful enough for solving partial differential equations that are needed for sound pressure field computation. Such software provides an efficient tool to analyze sound pressure level in a room, especially at low frequencies where statistical considerations are not convenient.*

1. INTRODUCTION

The area of active sound control has developed very fast during the last two decades, and a number of successful, practical applications are obtained. Nowadays, there are companies that, using standard procedures, are solving noise reduction in factories, transport and civil engineering. Main initiators of this development were the development of control theory, and cheaper electronic circuits for digital signal processing. Further progress of the application of active noise control in real systems is being slowed down, but the interest of the manufacturers for this technique is still increasing [1,2,3].

The main purpose of the active sound control is to provide higher noise reduction at low frequencies. In praxis, active noise control is being used only at low frequencies, while at higher frequencies standard solutions are applied, and they are based on the

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application of absorbing properties of the materials. In some of cases, active noise control provides higher noise reduction than the passive control. Sometimes, an efficient noise reduction is possible only by active control. It usually happens in tubes, when the frequency has to be low enough to excite only plane waves. In rooms, a noise control is possible only based on low frequency modes that have to be known. At middle and high frequencies, active noise control is hard to implement because there are different phenomena of sound propagation.

More complex digital signal processing, that is employed to achieve as efficient as possible active control, will not be considered in this paper. Since the effect of active control depends on used digital processing of signal originating from the secondary source, the active control is getting more efficient and applicable as the signal processing is improving.

In this paper we will first analyze the modes distribution of a single source of monochromatic sound that is placed in two different places in a regular room (the most incovenient case from the modal point of view), being reverberant in one case, and in the other case it had absorbing ceiling - as a passive control. After that we considered the SPL in the same room if there are both mentioned sources (the sound field is generated by two sources that are placed in the center and corner of the room) - active control, so that is can be considered as one of the sources is secondary and is used to reduce SPL at the particular place in a room. The secondary source is in phase with the primary in one case, and in 180° out of phase in the other.

2. BASIC PRINCIPLES OF SOUND FIELD CONTROL

Basic principles of the determination and the reduction of Sound Pressure Level (SPL) in a room were known at the end of the nineteenth century. The reduction of SPL was usually done by using specially placed good absorbing materials. This is known as the passive control of SPL. However, the basic principle that active control is based on has been known for almost three decades. The first experiments are done in 70's in tubes that represents the simplest case. The sound originating from primary source is led to the secondary source through an adaptive filter. The position of the secondary source depends on the geometry of room or tube. A control microphone measures obtained reduction effect. In general, SPL between the primary and the secondary source is not reduced, but by the use of active control, one can achieve reduction of SPL in needed direction or in the covered zone [1,2,3].

Previous results in the area of active noise control in tubes show that it is possible to achieve significant noise reduction at low frequencies (up to 1000 Hz), and that was the main purpose of active noise control from the beginning. It become clear that active noise control can reduce SPL more than passive control. Besides, the protection by active tools is cheaper and technically simpler than classical, passive protection.

The problem of noise reduction in tubes is relatively simple, because there is propagation of sound waves along on axis at the frequencies which wavelength is much greater than the diameter of the tube. It is achieved to reduce the SPL for 20–40 dB at low frequencies, while the absorption of middle and high frequencies is done by passive control. The complete equipment for active sound control in tubes is made by a number of companies. Depending on noise spectrum, an adaptive filter is made, and places for secondary sources are chosen. We can say that active control in tubes is getting used more often and more successfully.

More complex problem is noise level reduction in rooms. This problem is very significant, but previous investigation is mostly based on theoretical analysis with a few experimental results. It was shown that only in case of low modal densities a reduction of SPL could be achieved at low frequencies, using complicated digital signal processing. More complex cases with higher modal densities were not even analyzed. Unfortunately, this is often happening in real conditions.

In order to apply active noise control more successful to the room at low frequencies, a modal control is mainly used, and the modal control can be successfully applied when the modes distribution is good enough defined at the considered frequencies [4,5,6]. In that case, every single mode can be successfully reduced by careful control of secondary source signal. It is to be noted that the position of secondary source relative to primary is very critical.

In general, passive noise control methods that employ the use of sound-absorbing materials are practical and most effective at mid to high frequencies. On the other hand, active noise control techniques are more efficient at low frequencies. The complementary strengths and weaknesses of passive and active noise control methods have motivated many researchers to develop a system that integrates both methods. Unlike that, the hybrid passive-active control of SPL in a regular room is presented in this paper

3. DISRIBUTION OF SOUND PRESSURE LEVEL IN THE ROOM

The modes distribution for the source of small dimensions compared to wavelength of emitted monochromatic sound having frequency 100 Hz (λ = 3.43 m) are analyzed in this paper. Two cases are considered: one, when this source is in the middle of rectangular room, having dimensions 5×5×5 m^3, and the other one when the source is in one corner of the room between two walls at the same height as the first case. The room is cube shaped, and that is the least convenient shape from the sound field point of view, because there are only few extremely excited frequencies, and because of a lot of degenerate modes, i.e. modes having the same frequency. Frequency response of SPL at a given point in this room when all surfaces perfectly reflect sound, if the room is excited with white noise having bandwidth of one octave (from 90 to 180 Hz), is shown in Fig. 1 (solid line). It can be clearly seen that there are only five extremely excited frequencies. Fig. 1 (dashed line) shows response of the same room in case of absorbing ceiling. One can see that the response is much smoother in this case. Detailed computation of these characteristics can be found in [5,6].

Based on the Fig. 1. one can see that there are five extremely excited frequnecies in whole octave band. However, in case of absorbing ceiling previously mentioned peaks are much less or do not exist at all. It should be pointed out that this stands for ideal cases (α = 0 and α_c = 1), while in real cases the response would be between those two extremes. Therefore, we decided to consider freqeuncy of 100 Hz, at which the response has approximately the same value for both cases.

The distributions of relative SPLs in a plane at height of 1.50 m for given room with sound source in the middle of the room and in the corner at 0.5 m from the walls at the same height as the previously case (2.5 m), when all walls, floor and ceiling are ideally rigid and perfectly reflect sound so that they have an absorption coefficient $\alpha = 0$, are shown in Fig. 2. The distributions of relative SPLs in same plane in room, but for the ideal case so, when it is assumed that the ceiling is acoustically processed so that has absorption coefficient of 1 ($\alpha_c = 1$), and all other surfaces are perfectly reflecting, so that $\alpha = 0$ for given frequency, are shown in the same figure. In this way on can easily analyze SPL as a function sound source position, as well as the influence of ceiling absorption - passive SPL control.

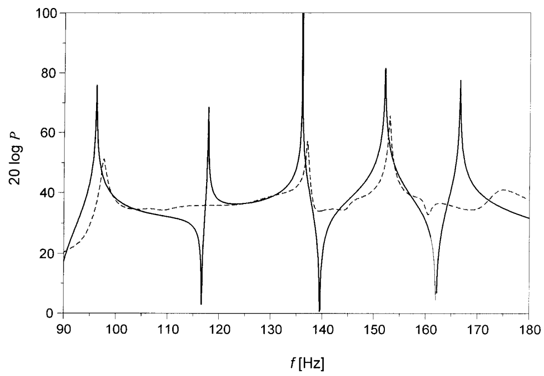
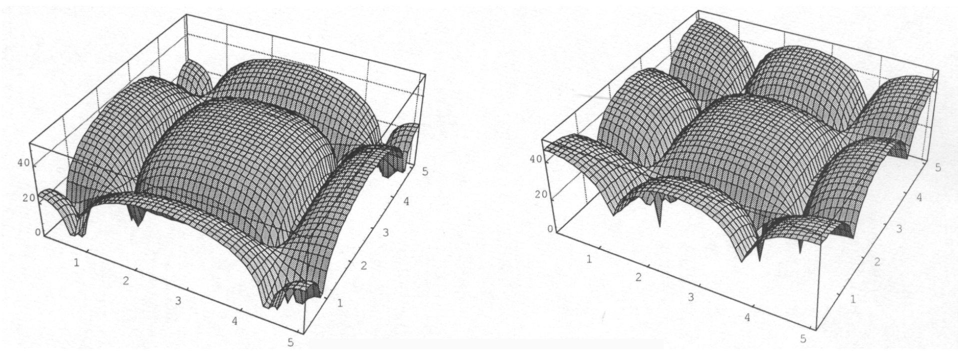


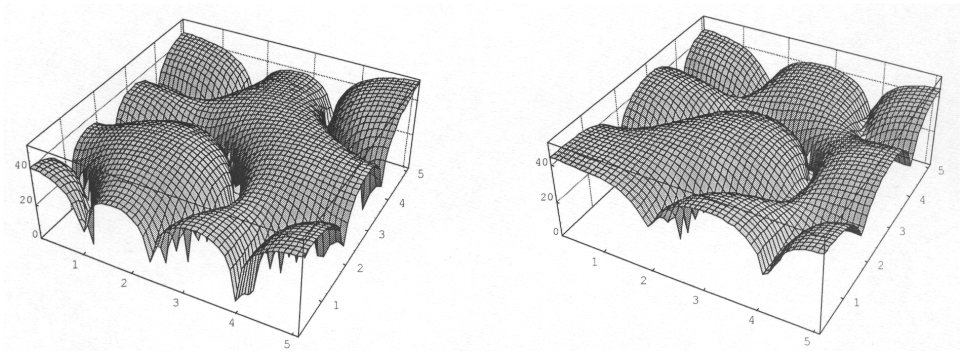
Fig.1. Relative SPL in a point in room 5×5×5 m^3 – all surfaces perfectly reflect sound (—) and only ceiling has absorbing coefficient of 1 (- - -)

If we consider the case that there are two simultaneously radiating sources, positioned at the previously mentioned places, in the center and the corner, then the resulting sound fields in the given plane are shown in Fig. 3, when sources radiate in phase and 180° out of phase. This case can be considered as that besides primary source, there is secondary that emits the same signal at 100 Hz, but in phase and 180° out of phase. In this way, kind of active noise control can be achieved.



Source in the center of the room

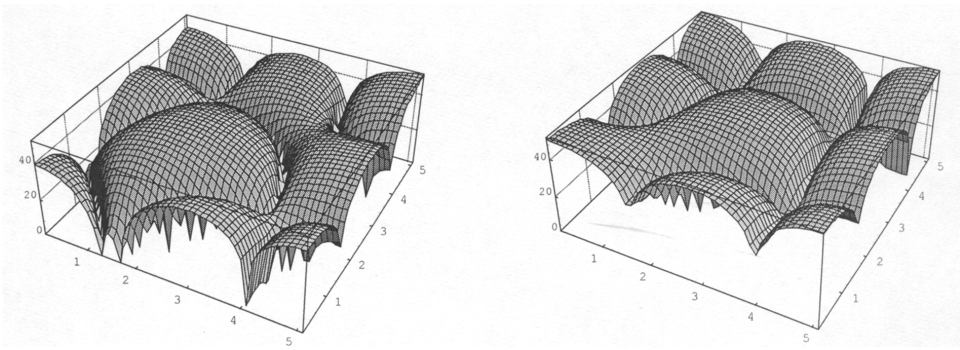
a) b)



Source in the corner of the room

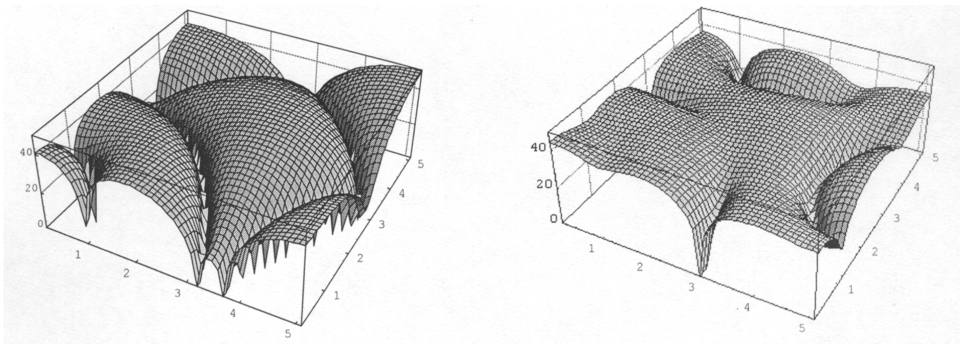
a) b)

Fig. 2. The distributions of relative SPLs in a plane in a room (5×5×5 m^3) when a) all surfaces are perfectly reflecting, so that $\alpha = 0$, and b) when ceiling has absorbing coefficient $\alpha_c = 1$



In the phase sources

a) b)



180° out of phase sources

a) b)

Fig. 3. Sound field distribution in a room (5×5×5 m^3), when there are two sound sources in the center and the corner of the room, wich emited in phase and 180° out of phase when all surfaces are a) perfectly reflecting, so that $\alpha = 0$, and b) when only ceiling is changed with $\alpha_c = 1$

4. SOUND FIELD DISTRIBUTION ANALYSIS

Analysis of sound field in given room shows that when the sound source is in the center of the room then maxmal SPLs are the center of considered surface and in the middles of the walls (about 40 dB), while at the corners the SPL is relatively low (even 20 dB lower than the other). There are some places with very narrow surfaces where the SPL is much lower. It is interesting that for the case when the ceiling perfectly absorbs sound ($\alpha_c = 1$), sound field has maximums which are higher form those in previous case (it reachs up to 45 dB, and in previous case it was 40 dB), and the maximums are distributed in the center of the considered plane, at the middles of walls, as well as in the corners, Fig. 2.

In the position when source is placed at the corner of the reverberant room (0.5 m from the wall, height still 2.5 m), field becomes symmetrical relative to diagonal of the considered plane. It is interesting that the SPL at the room corners is much higher. Maximal SPL in the corner of the room where is the source is 40 dB, in the neighboring corners 45 dB, and in the opposite corner SPL is about 50 dB, the highest in whole the room. Values of other maximums in the room and at the walls are slightly less than 40 dB. There are some narrow parts having minimal SPL.

The surface with minimal pressure level nearby sound source disappeared when we used absorbing ceiling. Because of that, the field is more uniformly distributed. The other configuration of the field is almost unchanged, and differences between maximums and minimums are now less. The maximum in the opposite corner is also less and it is about 40 dB. That high is the SPL at the other corners, as well as the maximums at the middle surfaces of the walls.

Based on the considered field distributions, one can conclude that it is more convenient to put the source, making unwanted sound, in the corner, not in the middle, of the room, and, by appropriate use of absorbing material, reduce total energy in the room - passive control. Using such an analysis one can determine the positions of standing wave "nodes", where absorbing material would have the greatest influence on total energy reduction. In the considered room, those positions would be corners, especially the opposite corner, and middle areas of the walls at the considered height. However, in reverberant room corners are not appropriate for the positioning of absorbing material at the considered frequency.

It is interesting that the configuration of sound field with two in-phase sources is similar to the one formed with one source placed in the corner, except the differences between maximums and minimums are more pronounced, Figs. 2, 3. Even the levels in the room corners remained the same when all walls are perfectly rigid. However, in the other parts of the room, maximal levels are higher for about 5 dB.

These differences are especially emphasized in case of absorbing ceiling, when the SPL in all corners and at the middles of walls is about 50 dB. Here can be clearly noted the increase of SPL in whole room for more than 5 dB compared to the case with a single source in the room corner. In this case SPL is the highest compared to all other cases.

However, when sound sources are 180° out of phase, the resulting SPL distribution is completely different. Maximal SPL (about 50 dB) is located only at the room corner opposite from sound source, while all other maximums are much less (slightly above 40 dB) than in case of reverberant room.

The most uniform sound field distribution in this room is obtained with two 180° out of phase sound sources in the room having absorbing ceiling. SPL along the room diagonal where sources are located has very soft maximums and minimums, with several dB around 40 dB. There are just a few strong minimums having small area close to the wall.

7. Conclusion

Based on previous theoretical results, we can conclude that relatively good results can be achieved at the area of passive and active noise control. These results are clarifying the idea of significant noise reduction at low frequencies using active control. This can be also seen from the presented distribution of sound field in a room, which is computed using very complex theoretical analysis, shown in the Appendix. It was shown that on the basis of given sound filed distribution in a room, one can do adequate distribution of absorbing material - passive control, as well as position and signal of one or more of other sources - active control, in order to reduce the level of unwanted sound in a given area.

In small rooms, especially at low frequencies, when room dimensions are of the same order of magnitude as wavelength, statistical considerations can not be applied to the determination of the sound field. It is well known that in those cases in the room and at the wall surfaces there are zones of higher or lower sound pressure, that depend on standing waves configuration, i.e. modes, and, depending on that, the efficiency of absorbing material is higher or lower. At the places where the pressure is higher, the higher is the consumption of acoustic energy, with the same absorbing material impedance. The efficiency of a material is higher if the pressure is higher in the considered point. Therefore, the absorbing material should be placed at the places where maximal levels of sound field are predicted, i.e. at the edges of walls, in corners, and at the middle parts of the walls. This means that one need to know modal density and sound field distribution, in order to implement passive control.

We should also point out that it is not difficult to reduce noise level at one frequency, or in the narrow frequency band. However, it was shown to be difficult to achieve significant reduction in wide frequency range, because of sound filed complexity.

Starting form the fact that a number of research centers in the world pays more attention to this problem and that there are a lot of paper being presented about this problem, we could expect more significant result in a short time. Very helpful, for solving this problem, is developed computer software for predicting the distribution of sound filed depending on the emitted sound characteristics, the position of sound in a room, as well as room characteristics, its dimensions, position and properties of the absorbing material, etc.

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SMANJENJE BUKE U PROSTORIJAMA POMOĆU AKTIVNE I PASIVNE KONTROLE NA OSNOVU MODALNE ANALIZE

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U ovom radu su izložene neke prednosti i nedostaci aktivne i pasivne kontrole buke u prostorijama na niskim frekvencijama. Primeri opisani u radu odnose se na analizu zvučnog polja na osnovu modalne analize u clju smanjenja nivoa zvuka u pojedinim oblastima prostorije pomoću postavljanja sekundarnog izvora - aktivna kontrola, kao i analiza smanjenja nivoa istog zvuka u istoj prostoriji, ali sa apsorbujućom tavanicom - pasivna kontrola. Osnovna svrha ovog rada je da pruži informaciju o nekim praktičnim aplikacijama aktivne i pasivne kontrole zvučnog polja, sa posebnim osvrtom na prednosti detaljne modalne analize koju danas omogućuju računari uz pomoć softvera za analizu zvučnog polja.