Transducers for Active Noise Control; practical considerations for product integration and manufacturability

Paul Darlington, Pierre Guiu, Mickael Lefebvre

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P Darlington[1], P Guiu[1], M Lefebvre[2]

[1] Phitek Systems (Europe) Sàrl, 34 Avenue du Léman, Lausanne, 1005, Switzerland, paul.darlington@phitek.com

[2] Phitek Systems, 28F, Block A, Southern Securities Building, Jian She Road, Shenzhen, China

Phitek Systems manufacture a wide range of commercially successful personal audio delivery platforms all of which include active noise control. The transducers in these systems include miniature electro-dynamic actuators and electro-static sensors, which are close-coupled into assemblies small enough to operate in the ear. This paper reviews some aspects of transducer function within an active control system, with particular emphasis on frequency response, dynamic range, linearity and self-noise. However, it is the main purpose of the paper to illustrate how the demands imposed by these objective criteria are exaggerated and exacerbated in the context of practical volume manufacture for the consumer market. The additional complexities of sample-to-sample variance in transducer performance are considered from the perspectives of system impact, quality control and manufacturing yield. Finally, examples of how system performance can be compromised by transducer handling during manufacture are presented.

1 Introduction

The transducers required to exert active control of sound include actuators to impose control action and sensors to observe the efficacy of such action. The actuators, which we shall refer to collectively as loudspeakers, and sensors, which we name microphones, are selected to have frequency response, sensitivity, power handling and linearity appropriate to the system under control and – particularly – appropriate to the controller technology available to us. In research activity, the transducers may be chosen so as to be at least sufficient for the tasks of observation and control. In a manufacturing context, the transducer choice is constrained, potentially compromising observation and limiting control.

Whilst it is possible and instructive to pursue a general description of Transducers for Active Noise Control, the present paper arises from a particular context; the design and manufacture of personal audio delivery systems with active noise reducing ('ANR') functionality. This context both constrains the transducer choice and performance and introduces some particular practical considerations for integration into an attractive, manufacturable product. Within this context, the transducers will be judged not just on their sufficiency for observation and control, but will also need to satisfy commercial considerations in which the value of the active noise reducing function must be seen to outweigh the cost of its provision so as to admit profitability. We go on to examine some of the particular considerations of the personal audio application.

2 Active Control in Personal Audio Platforms

The transducers in headphones and earphones used for personal audio delivery will share the task of exerting active noise reduction with their primary task of reproducing sound. This will place a series of performance demands on the transducers – particularly the loudspeaker – in order to present attractive audio quality. Additionally, the loudspeaker ought to be selected and driven in such a way as to ensure acoustic safety. These considerations are not incompatible with the provision of active noise reduction and we shall not examine them further, save to observe that transducers intended only to support narrow-band voice telephony applications ARE NOT APPROPRIATE.

2.1 Size

Headphones and earphones are small devices which acquire competitive advantage if they are smaller than similar items in the marketplace. Headphone platforms are of the order of 100 cc in volume (per side, for a circum-aural design), whilst earphones need to target physical volumes of < 2 cc if they are to allow true in-ear placement.

The market pull towards smaller headphone solutions presents a technical challenge in ensuring appropriate low frequency control and leak tolerance, whilst the latter volume presents challenges for the in-ear application of active control, particularly if feedback control topologies are chosen (see section 2.2).

2.2 Feedback Control

When a (non-adaptive) feedback control system is selected for a personal audio application, a microphone is implied inboard of the loudspeaker. Whilst easy to accommodate in a headphone platform, this requirement occupies almost half of the available volume of an in-ear application as, although microphones an order of magnitude smaller in volume than miniature loudspeakers are available, there needs to be provided an acoustic space in which the microphone operates.

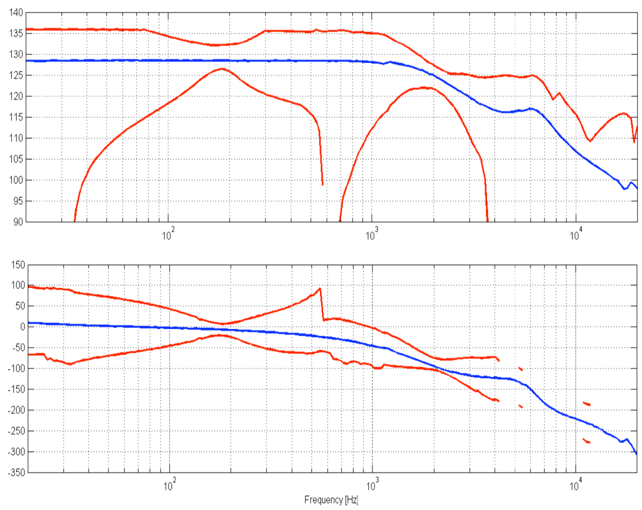
2.3 Contemporary Transducer Technology Choice

The selection of appropriate technology for the transducers in ANR-enabled personal audio delivery platforms is influenced by at least three factors; performance, size and cost. At the time of writing, these factors are balanced by the application of direct radiating dynamic loudspeakers and electret condenser microphones.

3 Transducer Specification

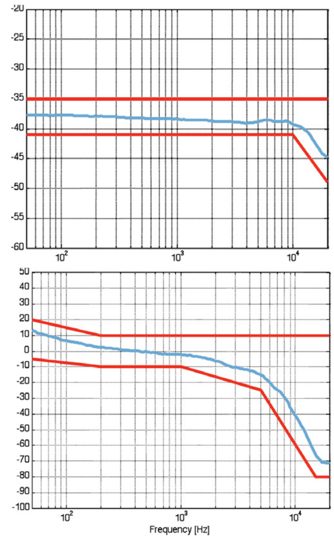
The transducers selected for application in any Phitek product are specified with reference to objective performance targets derived from analytical consideration of system-level performance. The details of this procedure are commercially confidential, but yield performance masks into which individual components and sub-assemblies must fit to conform.

Most importantly, the transducers' frequency responses, as measured in a standard specified test environment (NOT the operating environment), are defined by a nominal complex response and acceptable deviations expressed, for convenience, as gain and phase deviations. These are exemplified by Figures 1 & 2, which show gain and phase bounds (in red) and a nominal response (in blue) for a loudspeaker and microphone, respectively.



Figures 1 : Typical Frequency Response Bounds for a Loudspeaker, including Gain (upper) and Phase (lower), Nominal (blue) and Limits (red)

Note that the microphone response mask is significantly simpler than that of the loudspeaker, in consequence of the simpler passband dynamics of the microphone and the simpler test environment in which the response is specified. Note further that the loudspeaker mask includes some frequencies where limits are not defined, reflecting "don't care" status.



Figures 2 : Typical Frequency Response Bounds for a Microphone, including Gain (upper) and Phase (lower), Nominal (blue) and Limits (red)

4 Transducer Performance

We proceed to consider some of the particular aspects of transducer function important to successful commercial application of active control within personal audio ranging from the linear dynamics of a physical transducer, through the inevitable nonlinearities of a practical device to the undesirable operation as a noise source.

4.1 Linear Dynamics

The transducers used in active control are physical objects and subject to the ordinary constraints of dynamic systems. However, they are designed so as to encourage linear, time invariant behaviour. It is, in all cases, preferable if the dynamics of such behaviour is as simple as possible – complexity in transducer dynamics will at best have to be balanced by complexity in controller design and will at worst limit control action. In the case of transducers used with a canonical "feedback" noise cancelling scheme, the controller dynamics form a factor of the open loop response of the system, which at once controls active cancellation and determines stability limits. The linear dynamics, therefore, are of primary importance in selecting a transducer.

These linear dynamics are usefully decomposed into two factors; sensitivity and frequency response. The sensitivity may be interpreted as an overall scaling factor for the transducer response, whilst the frequency response function (expressing both gain and phase components) describes how the dynamics impose frequency selective behaviour.

The linear dynamics of a microphone play a far less important role in transducer selection than the dynamics of a loudspeaker. This is because the microphone is conventionally exploited at frequencies well below its first mechanical resonance, making the response that of a simple stiffness-controlled system. Accordingly, microphone selection is made primarily on the basis of nominal pressure sensitivity (V/Pa) at a convenient frequency (conventionally 1 kHz) with secondary reference to a frequency response limit, as exemplified in Figures 2. Typical manufacturing tolerances of +/- 3dB on the sensitivity can be adjusted by trimming the gain of the electronics. A number of contemporary microphones, especially those designed for mobile telephony or hearing instrument application, are found unsuitable for active control applications due to a high-pass characteristic limiting very low frequency magnitude response (and incurring the associated phase penalties). This feature of the microphone response may have been introduced to protect against the damaging effects of very low frequency pressure changes, which can saturate the microphone electronics (see section 4.2).

The loudspeaker, used through and above the frequency of its first mechanical resonance, has far more complicated linear dynamics and a more complicated frequency response function. It becomes difficult to use a standard sensitivity metric in such circumstances. Rather, the loudspeaker is selected primarily according to conformity with limiting bounds on a target frequency response function which will vary significantly between one application and another (see Figures 1). Unfortunately, the application may place the loudspeaker in an operating environment very different from industry-standard test environment, making specification, selection and parameterisation difficult. This is re-visited in section 5.1.

4.2 Non-Linear Dynamics

Both microphone and loudspeaker express nonlinearities in their mechanical and electro-mechanical behaviour, which complicates their application to active noise control. The nonlinearities constitute a signal-dependant noise source which ultimately limits control action.

Again, the impact of non-linearity is felt more strongly in the case of the loudspeaker than the microphone. The microphone has a distortion characteristic which rises with increasing applied pressure. Once a maximum operating pressure for the entire is specified, it is simple to select a microphone which has appropriately low distortion at this maximum pressure. The dynamic range of the microphone will then be controlled by its noise-floor, which is considered in section 4.3. It is important to note that in many active control applications, this maximum pressure may be experienced at very low (and, potentially, infra-sonic) frequencies, where the microphone may have distortion limits imposed by the electronics surrounding it (such as the source follower FET in an ECM).

The loudspeaker in an active control system will exhibit non-linearity associated with suspension, motor and diaphragm break-up. Each of these nonlinearities will introduce distortion effects, which must be managed if they are not to constitute a noise source which either limits the control action or (in the case of an audio application) compromises audio quality. The suspension and motor nonlinearities will also introduce hard-limiting effects, which limit the range of pressures over which control may usefully be exerted. Interestingly, many headphone systems include additional displacement limiting structures to control diaphragm excursion during large pressure change, indicating that the displacement limits on typical dynamic drivers intended for headphone application are often too liberal.

Specifying distortion limits for a loudspeaker in an active control application (particularly within personal audio) is complicated by the fact that the system may have far-from-flat frequency response. This can result in a misrepresentation of THD or THD + noise measures over frequency. As example, a transducer with substantially frequency-independent distortion driving a frequency selective system will return THD figures with peaks at frequencies where the system has dips in response and vice-versa. Accordingly, distortion figures measured as percentages of the fundamental are to be treated with caution. Practically, distortion limits are established for loudspeaker operation into standard test loads even though this may itself misrepresent the operating conditions of the final application (see section 5.1).

4.3 Self-Noise

Having considered the signal-related noise generation associated with nonlinearities, it is appropriate to go on to address noise generation independent of input signal. Loudspeakers are free of such undesirable behaviour, although the electronics which drive them certainly are not. Microphones, on the other hand, represent noise sources within an active control system.

In most cases, the thermal/acoustic noise generation in a microphone may be ignored in active control applications (although this is becoming an issue in the context of some of the very small microphones being considered for in-ear application). However, the microphone does include an active electronic component working as an impedance converter. This device is inherently noisy, making the microphone system a noise source in active control application (often the dominant noise source in a personal audio application). Accordingly, microphone selection is strongly influenced by consideration of self-noise, which imposes a lower limit defining the dynamic range of both the microphone itself and the entire system.

In summary, in contemporary applications of active control in personal audio, both loudspeaker and microphone systems are selected to offer suitable linear dynamics, with the loudspeaker choice further constrained by non-linear performance and the microphone selected with reference to self-noise generation.

5 Manufacture and Product Integration

In order for an artefact to be manufactured it must be specified. The specification must be accompanied by a test program sufficient to demonstrate conformity and the manufacturing process must capable of producing the conforming artefact at sufficient yield to make it commercially viable. These steps include significant challenges for the case of a transducer intended for application in a commercial Active Noise Control system.

5.1 Loading Conditions for Specification and Test

Aspects of transducer specification have been mentioned in preceding sections of this paper, where it was noted that the specification is made within a standard test environment familiar to transducer manufacturers. Such test environments might include IEC 318 artificial ears for testing miniature loudspeakers and free-field testing for microphones). These test environments are potentially very different than the environments in which the transducers will be applied. This discrepancy is very important and widely misunderstood by practicing electro-acousticians.

The performance of an electro-acoustic transducer is NEVER fully described by a single transfer function. At best, a single transfer function must be accompanied by knowledge of the test environment in which that transfer function was made to have any value. Even then, it will not be possible to take a transducer, specified by a single SISO transfer function in one known environment and predict performance in another known environment (this is strongly true of the loudspeaker but – arguably – weakly true of the microphone, as power transfer is not involved in the latter case).

Unfortunately, most conventional metrics of electro-acoustic transducers are insufficient to fully describe the transducers they are supposed to define. This generates a significant task for the designers of active noise control systems, who must understand how the transducers must work in their target application, but translate this into a form appropriate for specification and testability. In the case of the personal audio application, this often results in specifications and test procedures being placed in a low-impedance context (such as the relatively large volume of an IEC 318) when the end application operates at much higher impedance. Unfortunately, the parameters of the transducer revealed in a low-impedance test might not be those dominating high impedance operation.

As example, Phitek uses “Two Port” parameterisations of its loudspeakers, a formulation in which input electrical parameters (voltage and current) are related to output acoustic parameters (pressure and volume velocity). This relationship is embodied in a 2*2 matrix of complex “transmission” functions. Two of these transmission functions are emphasised in a low-impedance test environment, whilst the other two dominate a high impedance application; standard tests are optimised to measure precisely the “wrong” parameters!

5.2 Manufacture, Durability and Longevity

Once a specification and associated testing regime is in place, the process of component manufacture or of assembly into completed systems is still able to change in such a way as to yield non-conforming samples. These may occur as individual outliers in a distribution or as a concentrated batch and can only be trapped by a continuous and rigorous quality control process. Examples of manufacturing yield problems for miniature loudspeakers include maintaining concentricity of components during assembly and failure or faulty application of adhesives.

The transducers need to be sufficiently rugged to survive storage and product assembly. Cases have been observed in which microphones have been stored in hostile environments, promoting premature ageing. Similarly, incorrectly applied assembly processes have been found capable of imposing sufficient strain on miniature loudspeaker frames to disturb the frequency response and induce non-linear behaviour. Both of these categories of problem are avoided by rigorous quality assurance of supply chain and manufacturing issues.

Once the product has been purchased, the transducers will be further stressed in use and ageing. This must be anticipated by the application of quality in the initial engineering design. There are stresses associated with normal use, such as the very large pressure transients to which the transducers in head- and ear-phones can be subjected during fitting and removing the device. There are environmental stresses, in which the noise cancelling device and the components within it may be expected to perform in a range of temperatures which the wearer could not tolerate. These changes will impose material changes, changes to electrical conductivity and changes in acoustic parameters, all of which will compromise the transducers and will result in degradation of control action if the implications of the operating envelope are not accommodated in the initial engineering design. Finally, there are the natural processes of ageing, such as the implications of the half-life of an ECM microphone’s charge, which modifies system behaviour as the component ages.

6 Conclusion

The requirements for the electro-acoustic transducers specified for a commercial application of Active Noise control go far beyond the implications of the central observation and control task. The transducers must also obey constraints of size, performance and, particularly, cost if they are to be used in a commercially viable product. In addition to attending to the requirements of the transducers in situ at the design stage, it is important to be able to specify the transducers within a test environment familiar to transducer manufacturing partners. Understanding the mapping between these two acoustic environments is a key factor in developing acceptable yields in system manufacture and is one example of the diligent quality processes which must be applied to launch successful product incorporating Active Noise Control technology.