ACTIVE NOISE CONTROL: A REVIEW IN THE CONTEXT OF THE 'CUBE OF DIFFICULTY'.

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Over the past twenty years active control of noise has developed into a mature research field and into a product for some technical companies. This paper reviews the current state of the art in both the research and development fields using the context of a *cube of difficulty*. The cube illustrates how the three physical quantities: frequency bandwidth, spatial extent and signal coherence, contribute to the difficulty of achieving control performance. The literature is reviewed and placed within the cube to reveal patterns in research and areas of further work.

INTRODUCTION

Active control of noise is no longer an esoteric research topic, it has been implemented many times in the *real world* [1] and has become one of the tools available to the noise control engineer. However, its limitations and subtleties are still misunderstood by many. The simple explanation of creating an *anti-sound* field has left many people disillusioned when faced with the difficulties of implementation. The development of a robust and simple active control system suitable for wide application has illuded many companies [2].

The successful implementation of active noise control is effected by three physical concepts; spatial extent, frequency bandwidth and correlation or coherence of signals.

Spatial Extent: This describes the complexity of the control problem in terms of spatial variables. This could be the physical size of the required zone of quiet or the dimensionality of the control problem. Global control of plane waves in a duct, [3] could be considered to have a large spatial extent as it is possible to cancel all the sound downstream of the error sensor by reflecting all the sound energy back along the duct. However the problem is only 1-D and so can be considered of fairly low spatial complexity compared to the case above the cut-on frequency of the duct [4].

Frequency Bandwidth: Control of sound over a large bandwidth is more complex than control of a single tone for a number of reasons. The time interval over which control actions need to be calculated is smaller at high frequencies, the response of the plant is more complex and the spatial variation is higher. Due to the linear relationship between frequency and wavelength, bandwidth and spatial extent are intrinsically linked [5].

Coherence: To control a sound field the controller must have inputs that are coherent with the primary field. This correlation can be limited for several reasons, such as the sound field has low spatial correlation, as in a diffuse field at a single frequency[6]. Note, that in this case the field is correlated temporally, as only a single frequency is present. The input and error sensors may be incoherent due to the sound field being unrelated in time. This is the case for random disturbances when the delay between input and error signals is longer than the correlation delay. Some control problems are difficult because both types of incoherence are present, as is the case with turbulent boundary layer noise [7].

These three parameters are related in figure 1 by the *cube of difficulty*[8]. In the next section of the paper, each face and vertex of the cube of difficulty is discussed in turn with respect to the literature. Some approaches to current problems in active noise control are described in section three. Control algorithms are discussed in the penultimate section.

1.1 THE CUBE OF DIFFICULTY

The cube of difficulty can be used to visualise the physical limitations of active control systems, but it is only a metaphor for the relationship between the parameters. The axis of the cube are spatial extent, frequency bandwidth and incoherence. At one corner is *control of a single frequency at one point in space* at the other apex is *global control of broadband spatially incoherent noise*. These corners can also be referred to as the *easy* and *very difficult* types of control problem.

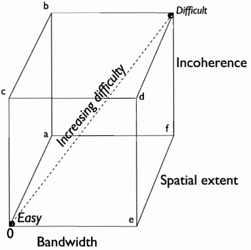

Figure 1: The cube of difficulty for active noise control.

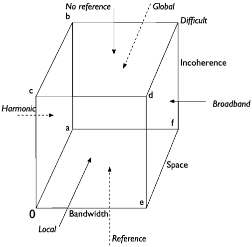

Figure 2: Problems in active control

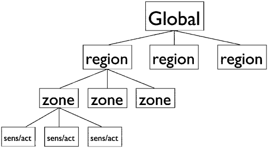

Figure 3: Possible active control system hierarchy based on division of space.

The '*0–c–d–e*' face: Local Control: The front face (*0–c–d–e*) represents local control. The most successful commercial application of active noise control, (noise canceling headsets), lie on this face.

Recent work by Jones [9] has shown that local zones of quiet can be created at a seat location, and that the neighbouring seat can also maintain its own zone of quiet or desired sound field.

The '*a–b–difficult–f*' face: Global Control: Global control is often sort after, and rarely achieved as it requires a significantly more complex control approach, especially at higher frequencies. The development of multi-channel control systems and associated high performance DSP chips has helped solve some of the control problems that lie close to this face. To appreciate the complexity of the problem it should be noted that multichannel control of random sound is not discussed until the final chapter of Nelson and Elliotts *Active Control of Sound*[5].

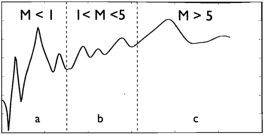

Figure 4: Possible active control system based on division of frequency.

The '*a–b–c–easy*' face: Harmonic Control: Feedforward control of single frequency noise was the focus of the Leugs patent[10], which is considered to be the first active noise control system. Harmonic control is also of greatest application to industry as the majority of noise sources are rotating machines.

The '*Difficult–d–e–f*' face: Broadband Control: These areas of active noise control have been investigated [11, 12] and have seen a huge increase in the number of successful applications due to the increase in computing power.

Noise sources that fall into this category are jet/flow noise, tyre/road noise and impact noise. All of which are difficult targets for active control systems. Reductions of up to 6dB in automotive interiors have been achieved by Park *et al.* [13].

The spatial coherence of broadband fields has been investigated by Chun et al [14] and Rafaely[15].

The '*0–a–f–e*' face: Control of coherent signals: Problems on this face are applicable to feedforward control. The sound field is coherent and so a reference is easily found. Feedforward control is more robust and can have a wider control band than feedback control, however digital hardware is usually required. Control of fan or propeller noise or any sound field where a coherent reference signal such as a tachometer output is available falls onto this face.

The '*b–c–d–Difficult*' face: Control of incoherent signals: If the sound field is incoherent over space/time, feedback control can be used. The error signal is used as the input to the controller, if the delays in the controller are small enough, the control output will be coherent with, and hence able to control the sound field. Feedback control of a large area is complex because multiple channels may be required. It is better suited to local control problems such as control of sound in headsets.

The use of multiple reference signals can help improve the control achieved. Often the sound field is due to many different sources; papers by Tu and Fuller discuss this issue [16, 17]. The problem of finding appropriate reference signals still exists. The use of multiple reference signals can cause instabilities if they are correlated with each other. This might be the case if they are structural or acoustic measurements. The method proposed by Tu pre-processes the reference signals to form a set of orthogonal signals which are then input to the controller.

The 'easy' corner: The lower left corner of the cube has been completed. Examples of local or 1-D control of single frequency noise can now be found in industrial installations and consumer products. It should be noted that on the left face of the cube, *i. e.* the single frequency face, the coherence axis refers to spatial coherence. Any single frequency is temporally coherent, however in a true diffuse field a harmonic signal will be incoherent over space.

Changes in bandwidth: The line from the origin to apex (a), represents single frequency control problems of varying spatial extent. Research by Rafaely [18] has shown that by specifically targeting a zone of quiet significant reductions can be achieved within that zone, as the extent of the zone increases more control effort and secondary sources are required.

Moving from the origin to point *c* is equivalent to increasingly the diffusity of the sound field. At point *c* the sound field only has a single frequency component and is the result of summation of many waves with random phases, as in an ideal diffuse field. The spatial correlation of diffuse fields is discussed by Rafaely [15].

The control bandwidth widens as noise control problems are located further along the *0–e* vertex. Increases in the control bandwidth have been obtained mostly by improved DSP performance. However some work on multi rate filtering has also yielded significant results [19].

Changes in spatial extent: The move from local to global control requires an increase in both the number of secondary sources and error sensors. Some success has been achieved by using virtual sensors [20]. However it is preferable to use good design, such as control of choke points [21] to achieve large areas of noise reduction.

Changes in signal correlation: At point *e* the sound field is coherent and so with a suitable reference and adequate actuators and sensors global control can be achieved. At point *d* a coherent reference no longer exists and so feedback must be used. Travel along this vertex is equivalent to the progression from control of propeller tones[22] to jet noise in aircraft interiors[23].

The *a–b* vertex represents the progression from global control of a harmonic/coherent signal to global control of a harmonic/incoherent signal. Point *a*, represents the global control of the sound field in an anechoic chamber, point *b* represents the global control of the sound field in a reverberation chamber. As most control systems act on a limited volume, we find these problems offset along the *b–c* vertex. An example of control of the sound field in a reverberant enclosure is given by [24]. It is shown that reduction of the global potential energy of the enclosure and maximum attenuation or extent of zones of quiet are not the same solution. This is inherent in active control problems.

Point *d* to the *difficult* corner: Control of spatially and temporally incoherent noise

The control of turbulent boundary layer noise was the focus of a great deal of work throughout the 1990s [7]. The turbulent boundary layer problem occupies space near the vertex (*d–Difficult*). The excitation is incoherent in time and space, and the required zone of quiet has to extend over many seats in the aircraft. This is a very difficult problem and it is accepted that control performance will decrease with coherence. Global, broadband control requires a complex control system and the performance is limited by many factors.

2 CURRENT PROBLEMS

2.1 Divide and conquer

An increasingly common approach is the subdivision of the controller into many smaller uncoupled units. Each unit controls a smaller, simpler problem, preferably one that is on the (*0–c–d–e*) face. Gardonio has applied this to vibration control problems [25, 26] and Mathur *et al* [27] have applied it to noise control problems.

2.1.1 Spatial Separation

Figure 3 shows how a control system could be split based on regions of control. The lowest level in the hierarchy is divided based on transducer coupling to the acoustic space.

This has been investigated by researchers such as Rob Clark[28] who investigated the effect of transducer location on modal observability and the use of spatially distributed sensors to reduce spillover between modes.

The *zone* level is based on the size of the zone of quiet and this level is split based on the interaction between zones of quiet[9].

The *region* level is divided as a function of gross system attributes, such as dividing the control problem within an aircraft into regions for the rear, wing/engine and front sections of the cabin.

The top level would be a scheduling and management layer. This layer could set weightings for individual regions or zones to maximise reduction in certain areas or make decisions based on hardware failure.

2.1.2 Frequency Separation

Figure 4 shows a division of the control problem based on frequency. Papenfuss *et al.* [29] demonstrated this approach for structural problems. The frequency range is split based on the modal overlap. In each region a different control scheme is applied. In the low modal overlap region optimal feedback controllers (H_2, H_∞) were used. In the mid frequency ∞ range where the modal overlap is between 1 and 5 an FX-LMS feedforward controller was used. In the high frequency range where only spatially limited control is possible a simple analog feedback loop was implemented.

The use of modal sensing or weighted transducer arrays is a form of selective sensing of frequency or spatial patterns [30][31] and has been applied to feedback control of structurally radiated sound.

2.2 Towards the upper right hand corner

Active control of sound now has two foci, implementation of established algorithms in *real world* applications and the continued pursuit of solutions to problems from the upper right hand corner of the *cube of difficulty*. As explained above reaching this corner is challenging due to the nature of the physical world. The divide and conquer approach may offer some solutions but these are likely to be highly theoretical and impractical.

3 IMPLEMENTATION

3.1 FX-LMS Feed forward

After its first proposal by Morgan[32] and independently by Widrow[33] the filtered-x LMS algorithm has been the mainstay for many active noise control systems. The reasons for this are: the algorithms ability to track changes on the same timescale as the delay in the error path, robustness to errors in the estimate of the error path, simplicity of implementation.

Reducing the computational load of feedforward algorithms has been the focus of much research, for example Bouchard *et al.* [34].

3.2 Feedback

Tseng *et al.* [35] have shown that by using optimal control techniques such as H_2 or H_∞ better control over the zones of quiet can be obtained. The H_2 approach will attempt to minimise the energy in the system and so is likely to be more robust than the minimisation of pressure at a number of discrete points. The energy density methods [36, 37] show similar results.

3.3 Neural Networks, Fuzzy Logic & Non-linear controllers

In an attempt to broaden the number of problems to which active control can be applied, linear controllers have been substituted by neural networks and fuzzy logic controllers. The neural networks have been used for system identification and the creation of the control outputs[38]. [39].

4 SPILLOVER

The technologies developed for active control of sound have been applied to several problems that are not noise control problems at first glance. Virtual acoustics [40] [41] is one example. The virtual acoustics problem can be written in terms of the minimisation of an error function by combination of primary and secondary fields. Active noise control researchers are now applying their knowledge to this field [42][43][44].

5 LIMITS OF THE CUBE ANALOGY

The cube of difficulty is only one way of describing the way physical properties of systems effect active noise control. As such it cannot encompass the full range of phenomena that influence ANVC design. Non-linear and time varying plants are an example of factors that are not well described by the cube analogy.

6 CONCLUSION

The upper right hand corner of the cube is unobtainable, however the division of the complex problems near this corner into many simple problems is yielding some advance. It should be borne in mind that much of the cube has been successfully tackled, (at least in the laboratory). However the full transition of active noise control technology to the market place is still yet to happen. Development is the key to successfully crossing from laboratories to general use. Only close collaboration between research groups in industry and academia will achieve this. More important, is the identification of a *killer application* in which active noise control can fulfill its potential.

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