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SUBJECTIVE ASSESSMENT OF OFFICE MACHINE NOISE

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1. INTRODUCTION

Modern office work tends to rely heavily on advanced machines, such as personal computers, photocopiers, and communications systems. Most of this machinery produces a certain amount of noise which, whilst not in general likely to be injurious to health, certainly has potential to cause distraction and annoyance, particularly to people who are not actually using the machine at the time. The sounds produced by a machine such as a photocopier can be a significant factor in an overall assessment of its performance. The sounds generated by a photocopier are produced by a number of different parts within the machine which change in importance with time as the machine goes through various cycles of operation. Unfortunately, the widely used dB(A) scale has only a relatively poor correlation with subjective impressions of complex noise sources which change over short periods of time.

A simulation technique has been developed to enable the subjective noisiness of office machines to be studied in greater depth. The sounds produced by the simulator can be experimentally manipulated and controlled in a way that would not be practicable by applying engineering modifications to a real machine. The long term aim of the research is the development of objective measurement and assessment techniques which will be able to provide reliable predictions of the subjective noisiness of future machines.

A number of alternative simulation techniques were investigated before deciding on the multi-channel simulation described herein. A series of blind subjective comparisons were carried out to assess the effectiveness of the simulation as eventually developed, and the results are reported in this paper.

2. ELECTRO-ACOUSTIC SIMULATION

2.1 Simulation Method

The overall objective of this study was to provide an accurate simulation of the sound of a Ricoh FT4460 photocopier in terms of the spectral, temporal and spatial aspects of its noise output.

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Initial comparisons using both binaural and conventional stereophonic techniques showed that these methods were not capable of providing a convincing simulation, irrespective of the audio quality of the equipment used. Binaural stereophony gives inconsistent localisation cues when listener head movement is allowed, and does not allow for unambiguous localisation with a fixed dummy head position. Although out-of-head localisation can be achieved, it is very difficult to prevent an impression being formed of being surrounded by the various parts of the machine. Conventional stereophony using either coincident directional microphones or spaced omnidirectional microphones can be made to sound very good, yet still be totally unconvincing, particularly when the listener is allowed to move from the stereo seat.

The eight channel simulation technique that was eventually developed uses simultaneous close microphone recordings of each of the major parts of the machine, reproduced through a custom made loudspeaker array. Each loudspeaker corresponds to a major noise source on the real machine.

The technique provides the following features:

Correct Location of Major Noise Sources - Since each major noise source has its own corresponding loudspeaker, the location of the source on the simulator is the same as that on the real copier.

Insensitivity to listener position - The simulation is equally effective irrespective of the orientation of the listener to the machine.

Correct Reverberant Field Excitation - Because the noise sources on the simulator correspond to those on the real machine, the reverberant soundfield in the listening room is excited in a very similar way.

Isolation of Individual Noise Sources - Since each noise source has its own recording and playback channel, it is possible to manipulate each noise electronically for experimental purposes. Spill between channels at the recording stage places a limit on the extent to which modifications to individual noise sources on the real machine can be simulated but careful selection and positioning of transducers can minimise this problem to a large extent.

2.2 Noise Sources

The major noise sources on the photocopier are as follows:

1. Sorter mechanism.
2. Double sided copy unit.

3. Scanner mechanism.
4. Front panel vibration.
5. Entry of paper from paper cassette to main copier body.
6. Fan on rear of copier.
7. Auto feeder outlet.
8. Auto feeder inlet.

2.3 Recording Transducer Types and Positions

A number of different microphone types and positions were investigated and their respective merits assessed from the point of view of sound quality and isolation of the target noise source from other sources. Omni-directional, cardioid (directional) and shotgun (highly directional) microphones were tried at various distances from each noise source in order to optimise accuracy of sound pick-up, spatial imaging and isolation of sources between microphone channels. Of particular interest were the differences in simulation quality between different microphone distances and directivity patterns.

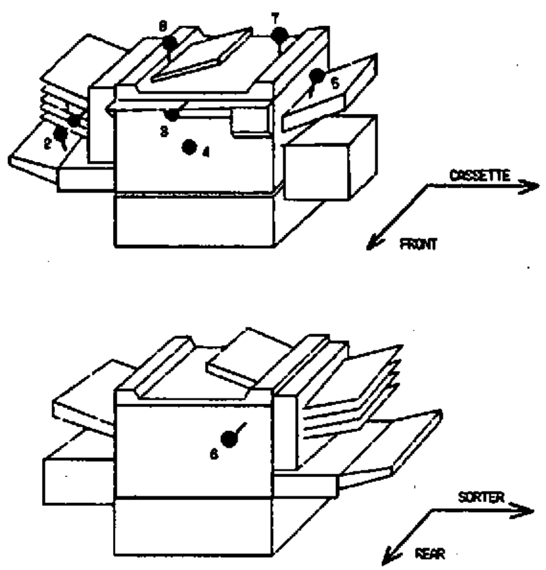
The miniature omni-directional microphones produced the best response both in terms of sound quality and of source isolation for the majority of noise sources provided that they were positioned very close to the sources. In principle, cardioid or super cardioid microphones can be positioned at an appropriate distance to limit coverage to the particular source of interest, but, in practice, the coverage angles are not uniform with frequency and off-axis pickup often displays unacceptable colouration when used for this purpose. Very close omni-mics can pick up an unrepresentative sound radiation pattern as they are effectively in the near field of many of the noise sources. Nevertheless, the smooth pressure response of the miniature omni-directional microphones selected for the simulator was found to yield a high quality audio signal which could easily be equalised to compensate for any response anomolies due to being placed in the near field of the sources. This equalisation process was used for the autofeeder where the spectral content was found to be more accurately represented by using a medium spaced cardioid microphone but the overall sound quality and source isolation was better using a close spaced omnidirectional microphone. One exception to this general rule was the front panel radiation, which was best represented by a vibration transducer fixed to its centre, in view of the size of the panel.

The final arrangement of transducers for the recordings consisted of the following:

1. Sorter - KEC BT1759
2. Double Sided Copy Unit - KEC BT1759
3. Scanner - KEC BT1759

4. Front Panel - KEC BU1771(vibration transducer) + h.f. roll-off
5. Paper Cassette - KEC BT1759
6. Rear Fan - KEC BT1759
7. Auto Feeder Outlet - KEC BT1759 + equalisation
8. Auto Feeder Inlet - KEC BT1759 + equalisation

Approximate positions for the microphones and vibration transducer are shown in Figure 1. A considerable amount of trial and error was involved in selecting the exact positions for the recording transducers.



< FIG1: MICROPHONE POSITIONS >

2.4 Recording and Playback

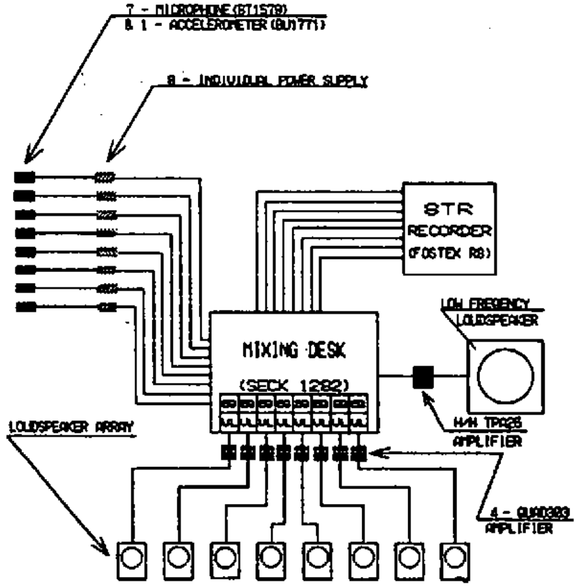
The miniature microphones used as recording transducers require low voltage power supplies and these were combined with switchable (0, 20, 40 dB) gain pre-amplifiers. During recording, the outputs from these pre-amps were connected via the line level inputs of a Seck 1282 mixing desk to a Fostex R8 8 track tape recorder connected to the desk at the channel insert stage. The precise level of signals going to tape could then be adjusted via the input gain control on the mixer in order to optimise the signal-to-noise ratio on the tape. Initially, recordings were carried out in the large anechoic room at ISVR to allow both close and distant microphone techniques to be compared. However, once the very close microphone technique had been established as preferable, this was no longer necessary and all subsequent recordings were made in the playback room as this allowed more ready comparison between the simulator and the real copier in a real listening environment.

On playback, the signals from the tape recorder entered the mixing desk at the channel insert stage. The level of each channel (signal source) was adjusted on the main channel faders and equalisation applied as necessary. The mixing desk provides a high frequency (11kHz) cut/boost, an adjustable mid-frequency (0.3-6.5kHz) cut/boost and a low frequency (45Hz) cut/boost. The output of each channel was then routed to the loudspeaker array via the 8 individually adjustable group outputs and an auxilliary send. Each channel could be monitored separately via the headphone output on the desk both at the input stage or following the equalisation. A schematic diagram of the equipment layout is shown in Figure 2.

2.5 Loudspeaker Array

A number of different arrangements were tried for the loudspeaker array used to represent the noise sources. Problems were caused because the noise sources on the photocopier typically have a much wider directivity pattern than standard loudspeaker designs. This was solved by the construction of 8 small loudspeaker enclosures containing a forward facing driver fitted with a parasitic high frequency cone and two piezo-electric high frequency units at plus and minus 90 degrees. Level controls on these auxilliary units were included to allow the high frequency directivity to be adjusted in accordance with the particular signal source. The complete enclosure design is shown in Figure 3.

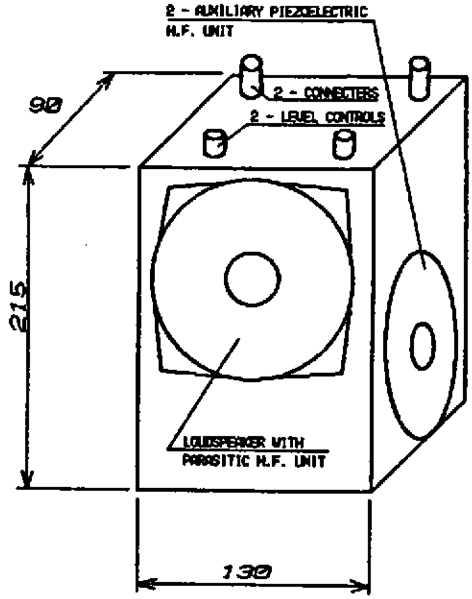
The design was optimised on the basis of size, which had to be kept to a minimum, frequency response and directivity. A small size was necessary to allow individual units to be mounted close together. The overall requirement was for a unit which maintained



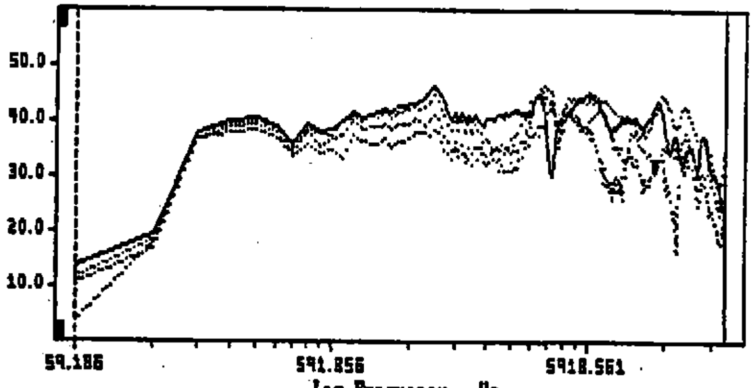
< FIG2: CONECTIONS >

a flat frequency response from 0.2 to 6 kHz throughout 180 degrees. This did have to be compromised to a certain extent in the final design, however, due to interactions between the high frequency units causing comb filtering at high frequencies. The frequency response of the loudspeaker at 0, 30, 60 and 90 degrees to the main axis is shown at Figure 4.

The loudspeaker units were powered by Quad 303 power amplifiers fed from the group ouputs of the mixing desk. A single 300mm diameter low frequency loudspeaker unit was fed from the auxilliary send on the mixing desk, via an HH TPA25 power amplifier, to provide low frequency reinforcement where necessary. A single loudspeaker was found to be adequate for this application as the ear is less sensitive to position at lower frequencies. The loudspeaker was positioned facing the rear of the simulator to reduce any high frequency information from the



< FIG3: SKETCH OF LOUDSPEAKER >



< FIG4: FREQUENCY RESPONSES >
(0,30,60,90 deg TO AXIS)

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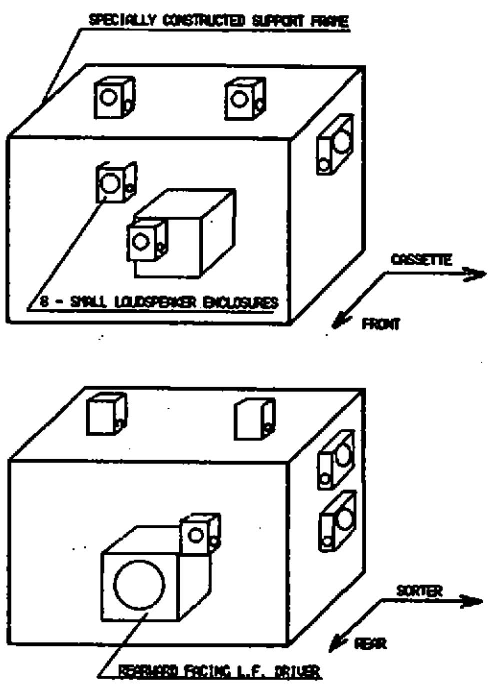
loudspeaker which could give conflicting locational cues to the main loudspeakers. Low pass filtering was not required as a result of this positioning. The amount of signal sent to this unit was adjustable for each recorded track, prior to fader and equalisation setting, using the pre-fader auxilliary send control on each mixer channel.

The loudspeakers were mounted on a specially constructed support frame which allowed them to be placed at positions corresponding to the noise sources on the copier. The amplifiers and low frequency unit were housed in the bottom of this structure. The complete design is shown at Figure 5.



< FIG5: DIAGRAM OF LOUDSP. STRUCTURE >

3. EVALUATION OF SIMULATION TECHNIQUE

3.1 Room Layout

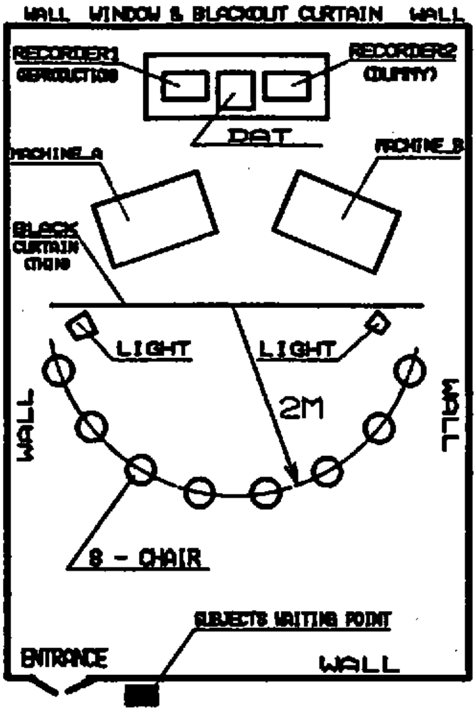
The simulator was evaluated by a comparison against a real machine in a 6m by 9.3m lecture room at ISVR in which subjects were asked to identify the real photocopier and comment on any differences and the reasons for their choice. The real photocopier and the simulator were concealed at one end of the room behind a curtain which was acoustically transparent to within 1dB between 20Hz and 20kHz. The machines were arranged, one to each side of the room, in such a way as to allow their positions to be reversed on succesive presentations to eliminate positional bias from the results. The approximate positions of the machines were labelled "A" and "B" on the curtain. The real machine and the simulator were presented alternately to one listener at a time who was free to move around the room. A second multitrack tape recorder was included with the experimental set-up and operated in conjunction with the real machine to eliminate tape recorder sounds as a possible identification cue. Fan noise, which is always present when the real copier is switched on, was replayed continuously through the lower front loudspeaker on the simulator, using a separate one hour digital audio tape (DAT) recording. The complete layout is shown in Figure 6.

3.2 Experimental Design

The order of presentation of the real machine and the simulator, the photocopier operation, and the positions of the real machine and the simulator within the room were balanced over 16 volunteer listeners. This was to ensure that every condition followed every other condition an equal number of times, each presentation order and machine location followed every other an equal number of times and that every condition was matched with each presentation order and machine location an equal number of times.

3.3 Experimental Procedure

There were eight male and eight female volunteer listeners. They were all staff or students at the University of Southampton and had all been found to have normal hearing within the last year. The test was carried out by two experimenters, one to operate the test equipment and one to elicit responses from the subject and to instruct the subject when to leave the room to enable the next presentation to be prepared. Care had to be taken not to allow the subject to see or hear any clues, other than those presented as part of the experiment, which would identify which machine was which. This meant that the listeners were required to leave and then re-enter the room between each and every presentation to allow the next presentation to be prepared (rewinding tapes or adjusting the real machine controls could have given unwanted identity clues).



< FIG6: ROOM LAYOUT >

All listeners were told that two machines were concealed behind the curtain, and that one was a real photocopier and one was a simulator designed to sound like the real photocopier. They were told that the purpose of the test was to assess the accuracy of the simulation by determining whether or not listeners could identify the real machine under a range of different operating conditions. They were not given any other clues as to the identity of the real machine except the sound. Each listener was exposed to the sound of both the real machine and the simulator under a particular operating condition and was then asked to say which machine they thought was the real copier (ie. A or B). They were also asked to comment on the reasons (if any) for their choice and any other points which they may have felt were relevant.

3.4 Results and Discussion
The results of the test are shown, grouped under photocopier operation, in Table 1.

TABLE 1 - RESULTS BY PHOTOCOPIER OPERATION

Subject	Photocopier Operation A	B	C	D
1	I	C	C	C
2	C	C	C	I
3	C	C	C	C
4	C	C	I	C
5	I	I	I	C
6	C	I	C	I
7	I	C	C	C
8	C	I	I	C
9	C	I	C	I
10	C	I	C	C
11	C	C	C	C
12	C	C	C	C
13	I	I	I	I
14	I	I	C	C
15	C	I	I	C
16	C	C	I	C
No. of correct identifications	11	8	10	12

A - Single copies of multiple sheets using auto feeder
B - Multiple copies of single sheet using sorter
C - Multiple copies of single sheet
D - Single double sided copies of multiple sheets using auto-feeder and double sided copy unit.

C = Correct identification
I = Incorrect identification

The real photocopier was misidentified a total of 20 times with "don't know" answers occuring 3 times out of the complete test of 64 comparisons. The Table shows that most errors occured for condition B, multiple copies of a single sheet using the sorter.

The real machine was identified correctly more times than it was not for conditions A, C, and D, but statistical analysis shows that the actual numbers of correct identifications were not sufficient (given the number of listeners) to prove beyond reasonable doubt that the listeners were not merely guessing at random. Starting from the null hypothesis that it is not possible to identify which is the real machine, statistical analysis using the binomial distribution indicates that the real machine could not be identified with greater than 95% confidence for any of the conditions except for the double sided copying condition. This had the lowest number of misidentifications although the real machine could not be identified with greater than 99% confidence.

Analysis of the results according to the presentation order reveals that, irrespective of machine operation, most errors occurred on the third presentation of the test although the real machine could not be identified with greater than 95% confidence for any of the presentation orders. Further analysis shows more errors occurring when the simulator was presented first than when the real machine was presented first and also when the real machine was on the left rather than when the simulator was on the left. However, the only combination of conditions (disregarding machine operation) where the real machine could be identified with greater than 95% confidence was when the real copier was presented on the right and first but it was still not identifiable with greater than 99% confidence.

Listener comments, as recorded during the test, suggested that the sound of the paper moving in and out was an important clue as to the identification of the real machine. This was initially surprising as this aspect had not been found to be lacking during preliminary evaluation of the simulator by the experimenters. In general, most listeners seemed to be basing a large part of their decisions on the overall 'smoothness' of the sound, and assumed that the real machine would be smoother sounding. Any sounds, whether real or simulated, which were either unfamiliar to the listener or unnoticed by the listener in previous experience of real photocopier sounds tended towards a bias against that sound as being 'real'. The apparent position of the separate noise sources on the machine was also a decision criterion for some listeners, although on two occasions listeners reported that the noise sources appeared to be too far apart on what was actually the real machine and then chose the simulator as being the 'real' machine. On one occasion the simulator was rejected as being too ideal and on another the real machine was rejected for the same reason. Any errors or extraneous noises in the operation of the real photocopier were noted by one of the experimenters during the test. Subsequent analysis showed that these factors did not affect the misidentifications of the real copier significantly.

It should be noted that the comparisons were not intended to measure the subjective magnitude of any differences between the real machine and the simulator, but merely to asses the extent to which the simulator could be accepted as a 'real' machine for use in further work. It would have been possible to spend a lot more time in developing the simulator, for example, by using sixteen or more recording channels, to make it completely indistinguishable from a real machine (by sound alone), but such efforts were not felt to be justified in terms of the degree of success which was achieved with an eight channel simulation. As developed, the simulator does not sound exactly the same as the particular photocopier being simulated, particularly to experienced ears, but it appears to sound sufficiently like a 'generic' real photocopier as to make a correct identification by an average listener problematical. It certainly does not sound obviously like a simulation in the way that a conventional stereophonic recording would.

4. CONCLUSIONS

A number of simulation techniques for the study of subjective impressions of office machinery noise have been evaluated. An eight channel simulator using close microphone recordings and a specially developed loudspeaker array was found to give the best simulation out of the available techniques. This simulator gives a good impression of the spatial separation of the various sources on a real machine, irrespective of listener position, and allows for the sounds to be readily manipulated under precise experimental control for future work.

The simulator was compared against a real photocopier in a single blind test where every care was taken to eliminate all cues to the identification of the real machine except the sounds produced under normal operations. The real machine was correctly identified more times than it was not, but statistical analysis shows that the correct identification rate was not significantly better than that which could have been expected from random guessing alone. This means that the simulator is sufficiently realistic as to be acceptable for future work on the subjective noisiness of office machinery.

Further tests are now underway, using the simulator, to assess the contributions to the overall perceived noisiness of each of the major noise sources within a real machine, and the subjective effects of changing the relationships between those sources with particular emphasis on the correlation with objective measures that take tonality, impulsivity, and irregularity into account.