A Digital Signal Processing Audiometric Workstation

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Abstract

In this paper we report on the development of *Digital Signal Processing Audiometric Workstation* based on a standard IBM PC and Motorola DSP56001 processor. The current system has functionality to test a patient's hearing using pure tone testing, FM tones, bandlimited noise, speech and white noise signals. Unlike most consumer DSP audio systems, the workstation uses 24 bit digital signals, which are then converted to analogue signals in an effort to produce a dynamic range much wider than the 88dB nominally achievable with 16 bit systems. Aside from the low level DSP functionality, the audiometric workstation has also been designed to be very easy to use by developing a Windows 3.1 based interface to provide a virtual instrument by duplicating the controls of a standard audiometer on screen.

Introduction

In this paper we present a digital signal processing (DSP) IBM-PC environment for audiometry. Audiometry is the practice of hearing testing, and is widely performed in:

1. Private practice for hearing aid fitting and dispensing;

2. In hearing research institutes to gain a better understanding of human hearing and methods of hearing impairment compensation; and

3. In industry where high levels of noise require that employees must be regularly tested to ensure that permanent hearing damage is not being done (compliance with UK and European health and safety guidelines).

Pure Tone Testing

A first test of any patient's hearing is usually performed by a pure tone audiometer, which is an instrument capable of generating very pure tones (less than 0.05% THD) over at test frequencies of 125Hz, 250Hz, 500Hz, 1000Hz, 2000Hz, 4000Hz and 8000Hz and dynamic ranges of almost 130dB for the most sensitive human hearing frequencies between 2-4kHz. A hearing profile can then be produced in dB HL (hearing level) to indicate the deviation from so called *normal* hearing [1], [2]. This profile is effectively a normalised graph, where the 0dB HL line represents the average *normal* limit of auditory sensitivity at the various frequencies.

Complex Test Signals

A simple audiometer can often only produce the above discrete frequency tones. More complex audiometers provide other intermediate frequencies, and also facilities for producing narrowband frequency modulated tones, narrowband noise, white noise, and speech noise, thus providing for a more involved investigation of hearing loss.

To date most audiometers are analogue standalone desktop instruments. They have traditional controls (dials, sliders, and switches) for controlling the various modes of the audiometer. More expensive audiometers have facilities available (RS232) for connection to a controlling computer or a printer. In general, however, most audiometers are still analogue instruments. The majority of circuitry inside consists of highly calibrated amplifiers and oscillators for producing the signals, with a minimal reliance on D/A converters.

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Digital Audio Standards

Over the last 10 years the consumer boom in digital audio has led to standardised sampling frequencies of 44.1kHz and 48kHz using 16 bit data. Although argued by a few analogue purists, it is generally acknowledge that consumer digital audio provides excellent hi-fidelity reproduction of music. A number of high end hifi companies also offer 18 bit and even claim 20 bit performance for CD players. This extended range is realised by interpolation of the 16 bit data to create more resolution. It therefore may seem obvious that audiometry could immediately benefit from these developments in digital audio. However there are two main reasons for this not happening:

(1) The dynamic range of 16 bit D/A converters is in theory 96dB. (In practice it is not much above 88dB.) Audiologists require up o 130dB of dynamic range at certain frequencies.

(2) Audiologists are reluctant to move from the easy to use desktop analogue audiometer, which they know to work very well, to a computer based system which can be rather intimidating to the non-computer literate audiologist.

Extending the Digital Audio Dynamic Range

At first thought it may seem easy to extend the dynamic range from 16 bits simply by using a D/A converter of more bits. This single chip D/A solution is however expensive, and to date 18-20 bits of real accuracy is the maximum companies will offer. (Each additional bit gives 6dB more resolution.) Another solution is to use an amplifier with about 40dB of gain that can be optionally switched in at the output when high level signals are required. This solution requires very accurately calibrated amplifiers and can cause problems when using complex signals in psyhoacoustic testing that require a very large dynamic range over a wide frequency range. This solution has however been incorporated into some early digital audiometers. Another potential solution is to use a 16 bit and an 8 bit converter and connect together using a scaling and a summing amplifier. This solution would require very accurately calibrated scaling amplifiers and is dealing with voltage levels well below the general noise level present in the circuits.

For the audiological workstation discussed in this paper, a very novel solution using a 24 bit Motorola DSP56001 PC hosted signal processing board has been developed. The technique is currently proprietry and will be the subject of future publications.

Interface to the DSP Audiometric Workstation

In order to make the Workstation easy to use, a *virtual instrument* has been created, whereby the controls of a standard audiometer are duplicated on the PC screen as illustrated in Figure 1. Currently all controls are mouse driven (point and click), although a touchscreen facility is currently under development. The Workstation can be used in a manual mode, and the operator will work the controls in exactly the same fashion as the traditional desktop instrument. The following test signals can be generated by the Workstation:

(1) Pure Tones
(2) Pulsed Tones
(3) Frequency Modulated Tones
(4) Narrowband Noise
(5) White Noise
(6) Speech Noise
(7) Speech From a Library of Data stored on the hard disk

The Workstation has also been coded with the procedures for hearing threshold detection, as outlined by the British Society of Audiology, allowing a near automatic hearing test to be performed. It also includes a full database facility with standard SQL search facilities which can be customised for the particular user; private practice, research, or health and safety hearing tests. Figure 2 shows the typical database features available for a hearing aid dispenser.

Accurate audiometer calibration is essential if standard testing is to be maintained. Therefore an easy to use digital calibration routine is available from the menu (see Figure 1), making it is less likely that accurate trimming of analogue amplifiers etc will be required.

Extended Dynamic Range for Speech Intelligibility Testing

One very important area of hearing research is speech intelligibility testing. One particular form of test is aimed at users listening to short sentences with a view to understanding the sentence meaning. In particular, similar words such as "car", "jar" and various disimilar words like "David" and "Michael" will be used in sentences and patients are invited to repeat the sentences, after they have been played at a variety of speech loudness levels, and with various levels of background noise. Many tests are now 16 bit digitised speech at 20kHz. If the researcher wants to play louder speech, then a digitally controlled amplifier is used to increase the speech volume in steps of 5dB.

One problem with the above test is that the louder presentation is actually unrepresentative of when a human speaks louder. The same word spoken at different levels: *quiet, soft, loud,* and *very loud* have completely different spectral characteristics. Therefore a more representative test would be to store the words at the required range of levels, which can be easily incorporated into the extended wordlength functionality of the Workstation.

Rapid Hearing Aid Evaluation

The Workstation has also been designed with a novel hearing *equalisation* facility. After a hearing profile has been realised, the workstation will allow the user to realise an inverse hearing compensation FIR digital filter in an attempt to correct the hearing to a *normal* level. It should be noted however that the ear is a very complex instrument and highly non-linear, and simple linear filter compensation is unlikely to correct hearing exactly. However it is anticipated that this novel feature can be used by researchers looking into hearing aid effectiveness and compensation. Alternatively the Workstation can store a number of hearing aid frequency responses which can be *inserted* and the hearing test repeated in order that the patient can quickly appreciate the effectiveness (or ineffectiveness!) of a hearing aid. (In general maximum benefit from an aid is not perceived until a few months of full time wearing, and hearing aid fitting in terms of frequency response shaping and ear-moulds is currently a very large area of research.)

The transfer functions of hearing aid earpieces (and even of simplified simulations of different listening environments with strong echo, reverberation etc) can also be easily inserted into the test signal path using the Workstation.

Conclusions

This paper presents an overview of the first generation design of a DSP based system for audiometric testing on a standard PC. Current 16 bit digital audio does not have the dynamic range required by audiometric testing, and therefore a novel method of extending the dynamic range has been developed for hearing testing using digital audio techniques. The current and future versions of the DSP Audiometric Workstation have been designed with reference to British audiological standards. A fully integrated database and hearing profile generation facilities have also been included. The workstation also features a novel hearing aid frequency response insertion facility to allow a quick evaluation of the likely effect of a hearing aid.

Acknowledgements:

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References

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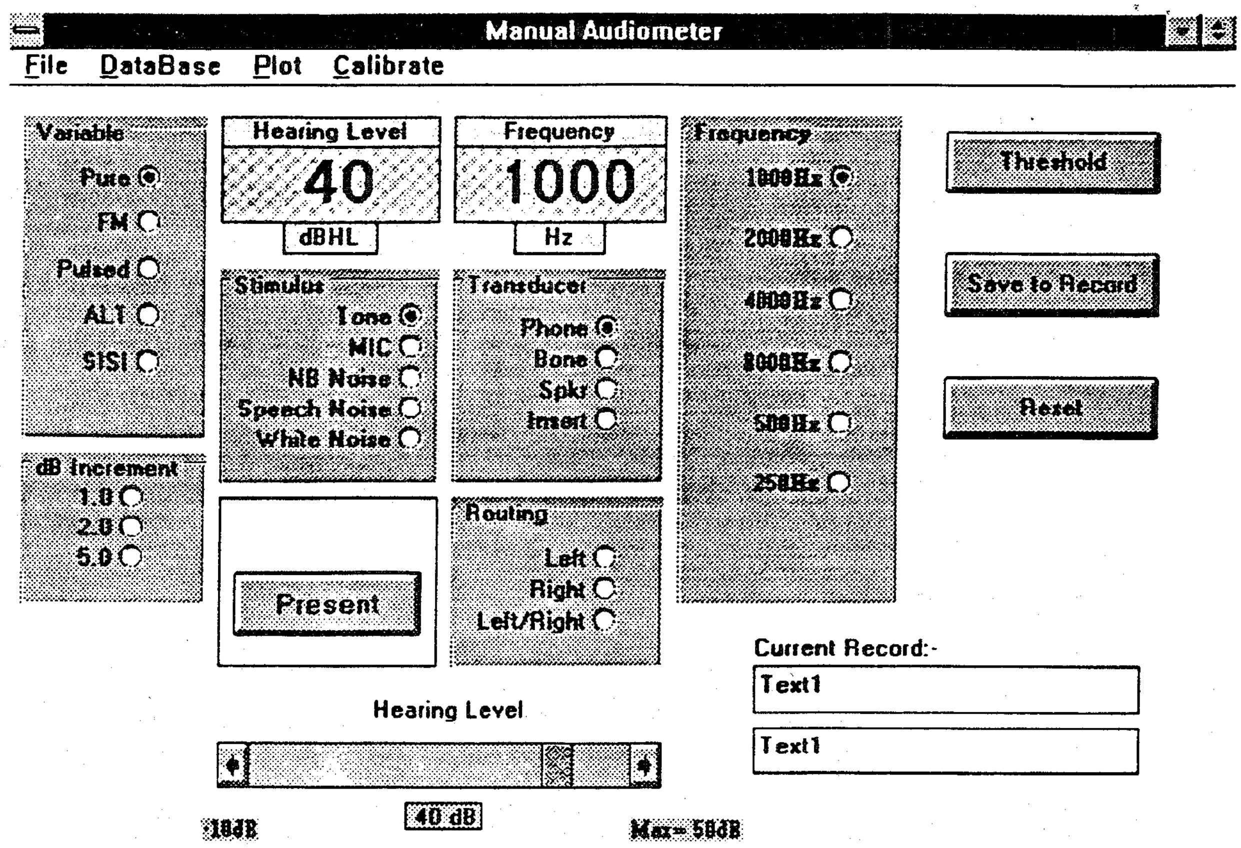

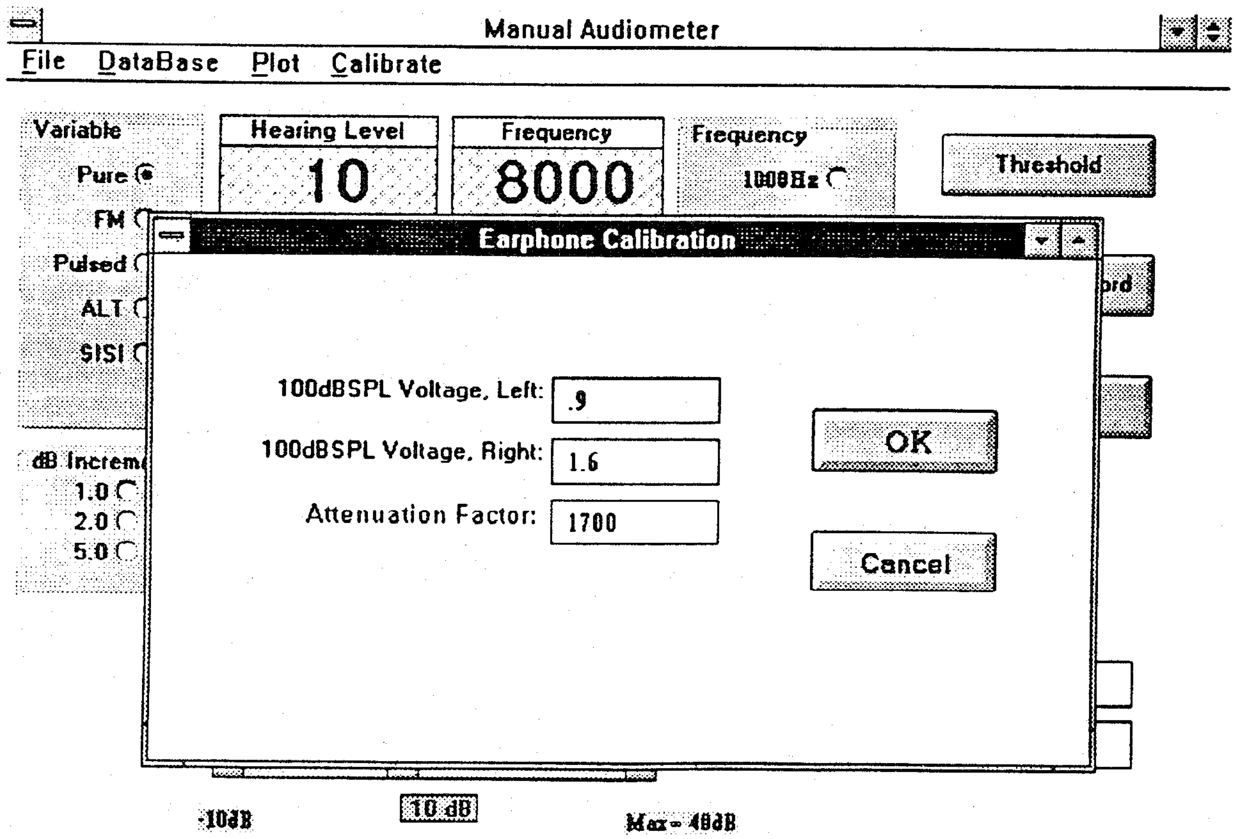

Figure 1: (a) Virtual Instrument User Interface (DSP Audiometer only)

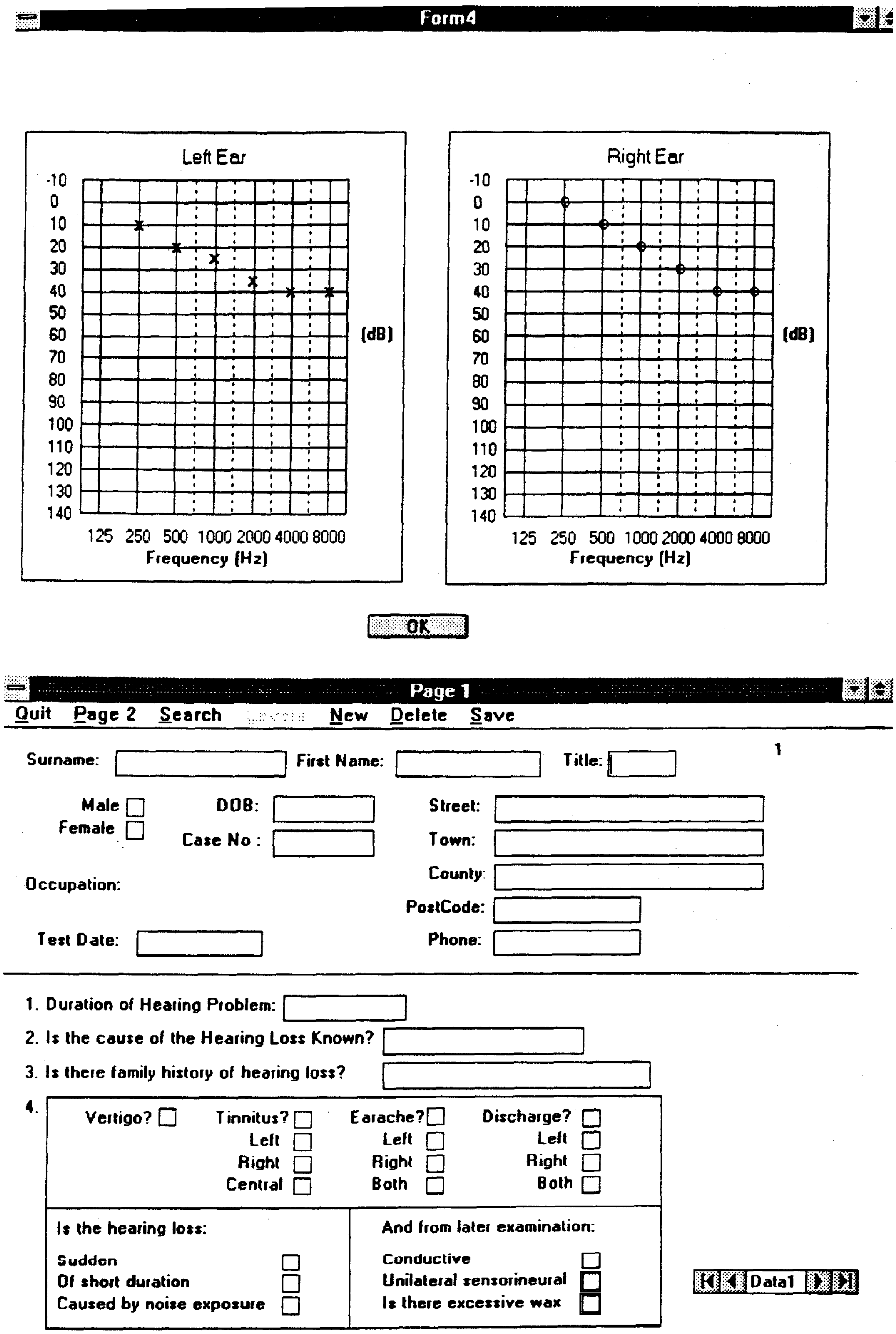

Figure 2: Example of integrated hearing aid dispensers database information.