Pulse Width Modulation (PWM) modules, which produce basically digital waveforms, can be used as cheap Digital-to-Analog (D/A) converters only a few external components. A wide variety of microcontroller applications exist that need analog output but do not require high resolution D/A converters. Some speech applications (talk back units, speech synthesis systems in toys, etc.) also do not require high resolution D/A converters. For these applications, Pulse Width Modulated outputs may be converted to analog outputs.

Conversion of PWM waveforms to analog signals involves the use of analog low-pass filters. This application note describes the design criteria of the analog filters necessary and the requirements of the PWM frequency. Later in this application note, a simple RC low-pass filter is designed to convert PWM speech signals of 4 kHz bandwidth.

In a typical PWM signal, the base frequency is fixed, but the pulse width is a variable. The pulse width is directly proportional to the amplitude of the original unmodulated signal. In other words, in a PWM signal, the frequency of the waveform is a constant while the duty cycle varies (from 0% to 100%) according to the amplitude of the original signal. A typical PWM signal is shown in Figure 1.

**FIGURE 1: A TYPICAL PWM WAVEFORM**

A Fourier analysis of a typical PWM signal (such as the one depicted in Figure 1) shows that there is a strong peak at frequency $F_n = 1/T$. Other strong harmonics also exist at $F = K/T$, where $K$ is an integer. These peaks are unwanted noise and should be eliminated. This requires that the PWM signal be low-pass filtered, thus eliminating these inherent noise components as shown in Figure 2.

The band-width of the desired signal should be

$$F_{bw} \ll (F_{PWM} = 1/T)$$

If $F_{bw}$ is selected such that $F_{bw} = F_{PWM}$, then the external low-pass filter should be a brick-wall type filter. Brick-wall type analog filters are very difficult and expensive to build. So, for practical purpose, the external low-pass filter should be as shown in Figure 3.

**FIGURE 2: FREQUENCY SPECTRUM OF A PWM SIGNAL**

This means,

$$F_{bw} \ll F_{PWM}$$

or

$$F_{PWM} \gg F_{bw}$$

$$=> F_{PWM} = K \cdot F_{bw} \quad (1)$$

where, $K$ is a constant such that $K \gg 1$

The value of $K$ should be chosen dependant upon the number dB the inherent fundamental noise component of PWM will be rejected. An example follows:

Example: It is required to design a simple RC low-pass filter to obtain an analog output from a pulse width modulated speech signal of bandwidth 4 kHz.

From eqn (1), choosing arbitrarily $K = 5$,

$$F_{PWM} = K \cdot f_{bw} = 5 \times 4 kHz = 20 kHz.$$
FIGURE 4: RC FILTER CONNECTED TO PWM1 OF PIC17C42

Choosing, the -3 dB point at 4 kHz, and using the relation $RC = \frac{1}{2\pi f}$, we get $R = 4$ kΩ, if $C$ is chosen as 0.01 µF:

- $R = 4.0$ kΩ
- $C = 0.01$ µF

Since the PWM frequency is selected as 20 kHz, the fundamental noise peak to be filtered is at 20 kHz. Now, let’s calculate by how many dB the main peak of PWM signal is cut-off at 20 kHz:

$$(dB) 20 \text{ kHz} = -10 \log[1 + (2\pi fRC)^2] = -14 \text{ dB}.$$
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## AMERICAS

**Corporate Office**
2355 West Chandler Blvd.
Chandler, AZ 85224-6199
Tel: 480-792-7200 Fax: 480-792-7277
Technical Support: 480-792-7627
Web Address: http://www.microchip.com

**Rocky Mountain**
2355 West Chandler Blvd.
Chandler, AZ 85224-6199
Tel: 480-792-7966 Fax: 480-792-7456

**Atlanta**
500 Sugar Mill Road, Suite 2008
Atlanta, GA 30350
Tel: 770-640-0034 Fax: 770-640-0307

**Boston**
2 Lan Drive, Suite 120
Westford, MA 01886
Tel: 978-692-3848 Fax: 978-692-3821

**Chicago**
333 Pierce Road, Suite 180
Itasca, IL 60143
Tel: 630-285-0071 Fax: 630-285-0075

**Dallas**
4570 Westgrove Drive, Suite 160
Addison, TX 75001
Tel: 972-818-7924 Fax: 972-818-2924

**Detroit**
Tri-Atria Office Building
32255 Northwestern Highway, Suite 190
Farmington Hills, MI 48334
Tel: 248-538-2250 Fax: 248-538-2260

**Kokomo**
2767 S. Albright Road
Kokomo, Indiana 46902
Tel: 765-864-8360 Fax: 765-864-8387

**Los Angeles**
18201 Von Karman, Suite 1090
Irvine, CA 92612
Tel: 949-263-1888 Fax: 949-263-1338

**New York**
150 Motor Parkway, Suite 202
Hauppauge, NY 11788
Tel: 631-273-5305 Fax: 631-273-5335

**San Jose**
Microchip Technology Inc.
2107 North First Street, Suite 590
San Jose, CA 95131
Tel: 408-436-7950 Fax: 408-436-7955

**Toronto**
6285 Northam Drive, Suite 108
Mississauga, Ontario L4V 1X5, Canada
Tel: 905-673-0699 Fax: 905-673-6509

## ASIA/PACIFIC

**Australia**
Microchip Technology Australia Pty Ltd
Suite 22, 41 Rawson Street
Epping 2121, NSW
Australia
Tel: 61-2-9886-6733 Fax: 61-2-9886-6755

**China - Beijing**
Microchip Technology Consulting (Shanghai) Co., Ltd., Beijing Liaison Office
Unit 915
Bei Hui Wan Tai Bldg.
No. 6 Chaoyangmen Beidajie
Beijing, 100027, No. China
Tel: 86-10-85282100 Fax: 86-10-85282104

**China - Chengdu**
Microchip Technology Consulting (Shanghai) Co., Ltd., Chengdu Liaison Office
Rm. 2401, 24th Floor,
Ming Xing Financial Tower
No. 88 TIDU Street
Chengdu 610016, China
Tel: 86-28-6766200 Fax: 86-28-6766599

**China - Fuzhou**
Microchip Technology Consulting (Shanghai) Co., Ltd., Fuzhou Liaison Office
No. 71 Wusi Road
Fuzhou 350001, China
Tel: 86-591-7503506 Fax: 86-591-7503521

**China - Shanghai**
Microchip Technology Consulting (Shanghai) Co., Ltd., World Trade Plaza
No. 787 Waiyuan Road
Shanghai 200001, China
Tel: 86-21-6275-5700 Fax: 86-21-6275-5060

**Hong Kong**
Microchip Technology Hong Kong Ltd.
Unit 901-6, Tower 2, Metroplaza
223 Hing Fong Road
Kwai Fong, N.T., Hong Kong
Tel: 852-2401-1200 Fax: 852-2401-3431

**India**
Microchip Technology Inc.
India Liaison Office
Divyacore Chambers
1 Floor, Wing A (A3/A4)
No. 11, O’Shaughnessy Road
Bangalore, 560 025, India
Tel: 91-80-2290061 Fax: 91-80-2290062

**Japan**
Microchip Technology Japan K.K.
Benex S-1 6F
3-18-20, Shinoyokohama
Kohoku-Ku, Yokohama-shi
Kanagawa, 222-0033, Japan
Tel: 81-45-471-6166 Fax: 81-45-471-6122

**Korea**
Microchip Technology Korea
168-1, Youngbo Bldg. 3 Floor
Samsung-Dong, Kangnam-Ku
Seoul, Korea 135-882
Tel: 82-2-554-7200 Fax: 82-2-558-5934

**Singapore**
Microchip Technology Singapore Pte Ltd.
200 Middle Road
#07-02 Prime Centre
Singapore, 189890
Tel: 65-6334-8870 Fax: 65-6334-8850

**Taiwan**
Microchip Technology Taiwan
11F-3, No. 207
Tung Hua North Road
Taipei, 105, Taiwan
Tel: 886-2-2717-7175 Fax: 886-2-2545-0139

## EUROPE

**Denmark**
Microchip Technology Nordic ApS
Lautrup høj 1-3
Ballup DK-2750 Denmark
Tel: 45 4420 9895 Fax: 45 4420 9910

**France**
Microchip Technology SARL
Parc d’Activite du Moulin de Massy
43 Rue du Saule Trapu
Batiment A - l\'er Etage
91300 Massy, France
Tel: 33-1-69-53-63-20 Fax: 33-1-69-30-90-79

**Germany**
Microchip Technology GmbH
Gustav-Heinemann Ring 125
D-81739 Munich, Germany
Tel: 49-89-627-144 0 Fax: 49-89-627-144-44

**Italy**
Microchip Technology SRL
Centro Direzionale Colleoni
Palazzo Tauro 1 V. Le Colleoni 1
20041 Agrate Brianza
Milan, Italy
Tel: 39-039-65791-1 Fax: 39-039-689983

**United Kingdom**
Microchip Technology Ltd.
505 Eskdale Road
Winnersh Triangle
Wokingham
Berkshire, England RG41 5TU
Tel: 44 118 921 5869 Fax: 44-118 921-5820

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