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EFFECTS OF TIME DELAY, ORDER OF FIR FILTER AND CONVERGENCE FACTOR ON SELF ADAPTIVE NOISE CANCELLATION

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ABSTRACT

When vibration analysis is used for bearing fault diagnostics in gearboxes, the accelerometer measures both bearing vibration and extraneous noise which may be discrete frequency and/or random. The bearing vibration appears in the spectrum as broadband frequency components because of its random-like characteristics and these may be masked by the gearmesh frequencies and their sidebands which are more discrete than the bearing components. In such cases a signal processing technique called "Self Adaptive Noise Cancellation" (SANC) may be used to separate the discrete and random-like vibrations. However the performance of this technique is controlled by the time delay, order of the FIR filter and the convergence factor and the optimal values for these variables depend on the particular signal.

This paper presents the effects of these three factors on the performance of SANC in separating simulated gear vibration signals (discrete frequency components) from simulated bearing vibration signals (broadband frequency components).

1. INTRODUCTION

Bearings are important components in gearboxes as the failure of the bearings may result in the seizure of the rotating parts or the improper positioning of the components which can lead to catastrophic results. An example is the failure of a bearing in a helicopter transmission gearbox which can lead to the loss of the aircraft. To counter such events, precautions such as vibration analysis have been used and proven to be viable in detecting faults in gearboxes (**1,3,4,6**). Since precautionary actions have to be taken before the actual failure of the gearbox, it is important to be capable of diagnosing incipient faults in the bearing so that its development can be monitored closely. However, since incipient faults are small in size and there are numerous gearmeshes (maybe up to 22 gearmeshes in certain helicopters) in the gearbox, the vibration signal of the bearing fault is often mixed with and masked by the noise. The noise may be discrete frequencies such as sidebands of the gearmesh frequency caused by modulation of the gearmesh due to any of the rotating shafts in the gearmesh. The noise may also be random though in a gearbox typically at a much lower value.

Since gear vibrations have a more discrete characteristic than bearing vibrations, adaptive filters such as Self Adaptive Noise Cancellation can separate the two using this property, as demonstrated in the case of a real helicopter gearbox (**5**). The SANC is essentially a FIR filter with a time varying transfer function that adapts to the signal conditions by having coefficients that change with time. SANC is in fact a special type of a more general technique called Adaptive Noise Cancellation (ANC). The only difference between ANC and SANC is that the latter only requires one input whereas the former requires two inputs.

2. CONCEPT OF SANC

A schematic diagram of the SANC system is shown in figure 1. The difference between the ANC and the SANC systems is in the way the two inputs are formed. For the former, two inputs are obtained from two vibration transducers and the adaptive filter can extract the component in the Primary Input that is most correlated with a component in the Reference Input. In using ANC for bearing diagnostics in the presence of gear noise, the primary input will contain the bearing signal (s_o) and gear noise (n_o) whereas the reference input will have gear noise (n_1) which is coherent with the gear noise in the primary input (n_o). Ideally there should be no component in the reference input that is coherent with the bearing signal in the primary signal (eg. by measuring the reference input at a remote location). Upon adaptation, the error (e) at the canceller output is the original bearing signal (s_o).

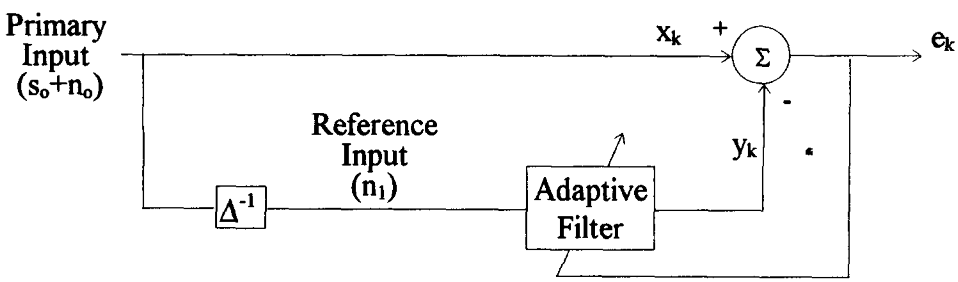

Figure 1 - Schematic Diagram of SANC

SANC does not require two vibration transducers and satisfies the reference input criteria by adding a delay to the primary input. As mentioned earlier, for bearing signals contaminated with gear noise, the bearing vibration component is random-like and the gear vibration component is deterministic. Upon applying an appropriate delay (Δ^{-1}) to the primary input to form the reference input, the bearing component in the reference input (s_1) will be decorrelated from those in the primary input. However the gear components will remain correlated because of their periodic nature. Thus, the criterion for the reference input has been satisfied and the error (e) should contain the bearing signal (s_o).

One can see that both systems contain an adaptive predictor and it removes the predictable component in the primary input leaving only the unpredictable component at the output.

A detailed explanation of the theory behind the adaptive canceller can be found in (**8**). In algorithmic form, the k^{th} value of the canceller output and the k^{th} FIR filter coefficient matrix can be written as:

$$e_k = x_k - y_k = x_k - \mathbf{B_k X_k^T} \qquad (1)$$

$$\mathbf{B}_k = \mathbf{B}_{k-1} + 2\,\mu_n\, e_{k-1}\mathbf{X}_{k-1}$$
$$= \mathbf{B}_{k-1} + \frac{2\,\mu\, e_{k-1}\mathbf{X}_{k-1}}{(L+1)\hat{\sigma}^2_{k-1}} \qquad (2)$$

where,

k - Variable designating the present iteration in the adaptive process
L - The order of the FIR filter ((L+1) is the number of filter coefficients)
μ_n - Normalized convergence factor
e_k - The k^{th} value at the canceller output
x_k - The k^{th} value of the primary input
y_k - The k^{th} value of the reference input
$\hat{\sigma}^2_k$ - The k^{th} exponential average of the input signal power
$\mathbf{X}_k$ - The input signal matrix : $\mathbf{X}_k = [x_k\ x_{k-1} \ldots\ldots x_{k-L}]$
$\mathbf{B}_k$ - The FIR coefficient matrix at the k^{th} iteration : $\mathbf{B}_k = [b_o(k) \ldots\ldots b_L(k)]$

Since the convergence factor μ varies according to the input signal power, it is normalised by the number of filter coefficients and the signal power to become dimensionless. This paper studies the effects of the delay (Δ^{-1}), convergence factor (μ_n) and the order of the FIR filter (L) on the adaptation process of the SANC in removing discrete frequency components from narrowband noise as experienced in a helicopter gearbox.

3. SIMULATION

For incipient fault diagnosis, the fault is presumably much smaller than the diameter of the rolling element. Therefore, the rolling elements tend to roll off the leading edge of the fault and impact with the opposite edge. The series of impacts between the edge of the fault and the rolling elements will result in the generation of a train of impulse responses. In the simulation, the train of responses was formed by joining a series of impulse responses of a single degree of freedom system in succession. The spectrum of this signal will be a series of discrete harmonics spaced at the ball pass frequency with the amplitude highest at the resonance frequency. The number of samples between each impulse response can be varied in order to simulate the random fluctuation of the interval between the successive impacts. This will cause the harmonics in the spectrum to smear with the possibility of higher harmonics overlapping with each other as occurs in practical bearing signals. When this occurs the energy is no longer concentrated in discrete components but spread to adjacent frequencies. This causes a reduction in the amplitude of all the frequency components and increases the possibility of masking by other discrete components. The simulation program can control the natural frequency, damping, pulse amplitude, ball pass frequency and the degree of random fluctuation between the impulse responses.

In the frequency domain, the bearing signal can be interpreted as having a carrier which is the resonance frequency and a series of sidebands spaced at the ball pass frequency. Therefore, by using envelope analysis or amplitude demodulation to detect the presence of the sideband structure, bearing diagnostic information can be obtained. The envelope spectrum contains effectively discrete frequency components even when they are obtained by demodulating a smeared carrier frequency as shown in (5).

In an actual gearbox, the interference from gear vibration takes the form of gearmesh frequency components and/or sidebands of these components which are spaced at either of the shaft rotation speeds of the gearmesh. These frequency components are phase locked with the rotation of the shaft. In order to simulate these gear vibrations, various discrete components were placed in the frequency range being amplitude demodulated. The simulation allows changes in the number of discrete components, and the amplitude and harmonic structure of the discrete components.

Frequency shift was used to reduce the sampling frequency of the bandpass signal because by decreasing the number of samples in the time record, the computation time for the SANC also decreases. The results given here are based on a sampling frequency reduction of 8:1 and data given in terms of samples per period will have to be adjusted proportional to the reduced sampling frequency.

Helicopter gearboxes are of special interest as they can have up to 22 gearmeshes and each one would produce gearmesh frequencies with sidebands spaced at the shaft rotation speeds. Typical gearboxes for helicopters with turbine engines have an input shaft speed of approximately 20000rpm (333 Hz) and faults have typically been found by demodulating in the range between the 40th and 50th harmonic. Thus the simulations reported here have been performed in this region for simulating typical cases.

Since the discrete components which contaminate the bearing vibration are typically spaced at the shaft speeds in the gearbox, the spacing of the discrete frequency components in the simulation varied from the rotor speed (the slowest) to the input speed (the fastest), typically a range of 1:65.

4. TIME DELAY

The SANC is based on applying a delay to the primary input so that the discrete components in the reference and primary inputs will be correlated and the random components in the two inputs will be uncorrelated. Therefore the minimum delay to use will be the delay required to give the random components a very low correlation compared to the discrete components.

Theoretically, the discrete components should have an infinite correlation length but in practice this is not the case because slight fluctuations in the shaft speeds of the gear train will result in a finite correlation length. However, this may be overcome if tracking (a technique for controlling the sampling frequency to be synchronous with a shaft phase locked tacho signal) is used to track the particular family of discrete components that is interfering with the bearing vibrations. This will make each frequency in the family lie exactly on an analysis line in the spectrum. This procedure is beyond the scope of this paper and therefore will not be discussed further.

For a narrowband random signal with a bandwidth equal to a certain percentage of the central frequency, the correlation length will be of the order of the reciprocal of the bandwidth. Thus the auto-correlation function will have a carrier at the central frequency and amplitude decreasing to zero at the correlation time corresponding to the inverse of the bandwidth (refer to figure 2).

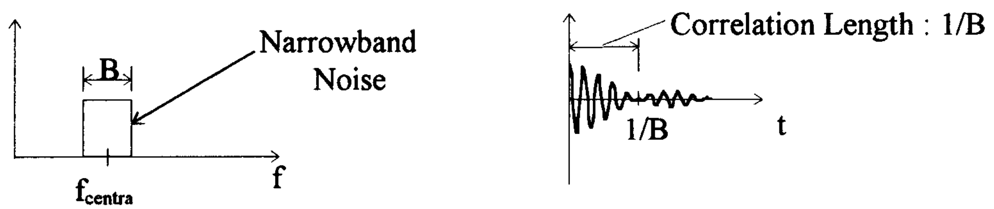

Figure 2 - Bandwidth and correlation length

For the bearing vibration signals generated in the simulation, if there is 1% random (normal random) variation in the spacing of the impulse responses, the bandwidth will be approximately 1% of the natural frequency which is the central frequency of the demodulation band. The inverse of the bandwidth will then be the correlation length and in this case it will be 100 periods of the carrier frequency.

From simulation results, by using the lowest FIR filter order which will attenuate the discrete frequency components, the choice of the delay should follow the guideline set out above. However when orders larger than the minimum are used, the dependency of the delay on the correlation length is not so strong as illustrated in figure 3.

Figure 3(a) shows the envelope spectrum before SANC, that is including all the discrete and narrowband random components. Figure 3(b) is the envelope spectrum after SANC performed at the lowest order with a delay corresponding to the inverse of the bandwidth of the random components. It should be noted that before SANC, the envelope spectrum is dominated by the gear modulations and the bearing harmonics are totally masked. After SANC, only the bearing harmonics are left. However when the delay used for the SANC was below the suggested minimum, the adaptive canceller could not attenuate the discrete components (refer to figure 3(c)). Figure 3(d) shows the envelope spectrum after SANC at a delay below the suggested minimum but with an order 5 times larger than the minimum order.

This is most likely due to the fact that the longer impulse response time of a higher order filter allows for the inclusion of an additional intrinsic delay in the filter response.

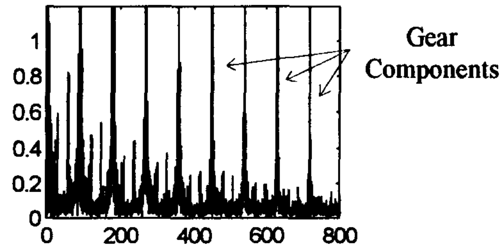

Figure 3(a) - Envelope spectrum of discrete and random components

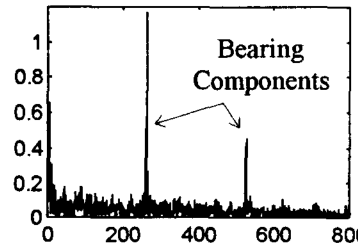

Figure 3(b) - Envelope spectrum after SANC, at $\Delta^{-1}=\Delta^{-1}_{min}$ and $L=L_{min}$

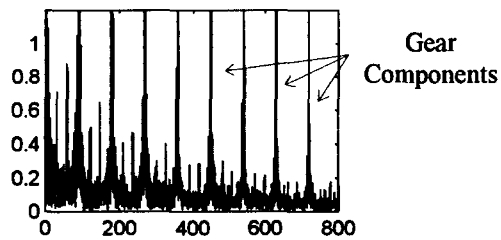

Figure 3(c) - Envelope spectrum after SANC, at $\Delta^{-1}<\Delta^{-1}_{min}$ and $L=L_{min}$

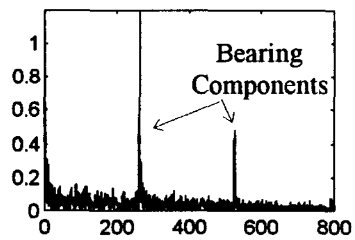

Figure 3(d) - Envelope spectrum after SANC, at $\Delta^{-1}<\Delta^{-1}_{min}$ and $L=5 * L_{min}$

In general, it is recommended that the delay should be set above the required minimum and as will be shown in the following section, the order should also be set a number of times greater than the minimum. Both of these conditions will ensure that the required delay is achieved.

5. ORDER

The FIR filter is responsible for filtering out the random components from the reference input so that only these random components will remain at the canceller output. In bearing diagnostics, this would mean the bearing to gear vibration ratio will be considerably higher at the canceller output than at the input.

In order for all the discrete components to remain in the adaptive filter output, the spectrum of the FIR filter must resemble a comb filter with the peaks aligned at the discrete frequencies and having an amplitude of one. The depressions between the peaks should be zero so that none of the broadband components from the reference input will appear in the adaptive filter output.

As explained in previous sections, envelope analysis or amplitude demodulation is the standard technique used to detect the presence of bearing components in the overall vibration signal. Usually the envelope spectrum will contain both gear and bearing components and there is a minimum order required by the SANC for the removal of the discrete gear components. Although the SANC is able to remove the discrete components with the minimum order, it does not recover the broadband components completely. This is because the adaptive filter with the minimum order is substantially different to the ideal adaptive filter, and broadband components are allowed to pass through from the reference input to the adaptive filter output but with a phase shift. Therefore by only using the minimum order, the bearing harmonics in the envelope spectrum of the canceller output may be distorted and an order 3 times larger than the minimum is recommended for diagnostic purposes.

The minimum order used for the FIR filter varies depending on the kind of signal that is entering the adaptive canceller, that is, the number and spacing of the discrete frequency components. However typical discrete frequency components that are present among the bearing components in a helicopter gearbox are sidebands spaced at approximately half the input shaft speed. This usually means there will be no more than 36 discrete components in a typical demodulation band used for bearing diagnostics.

There are really three main types of arrangements the discrete frequency components may have; only one discrete component, 1 family of equi-spaced components and a random arrangement of multiple components. By simulating the discrete components for the three general cases, a trend for the minimum order and the convergence factor can be obtained.

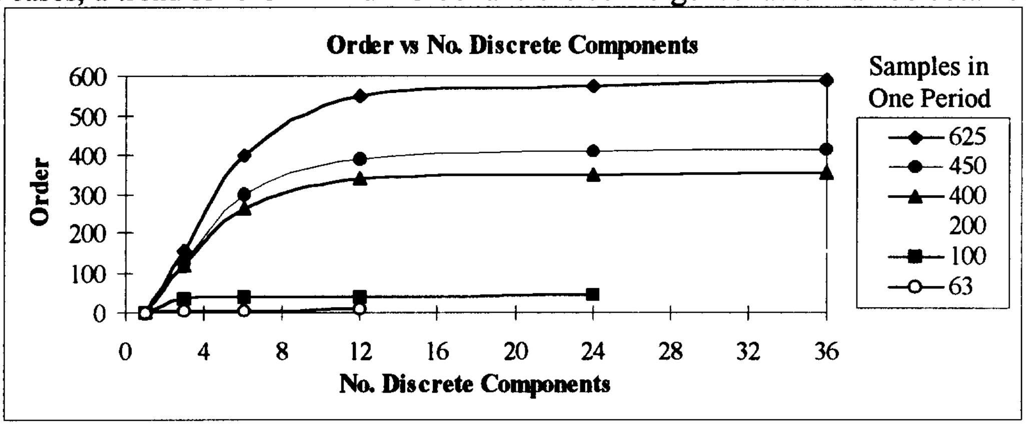

Figure 4- Minimum order vs number of gear components

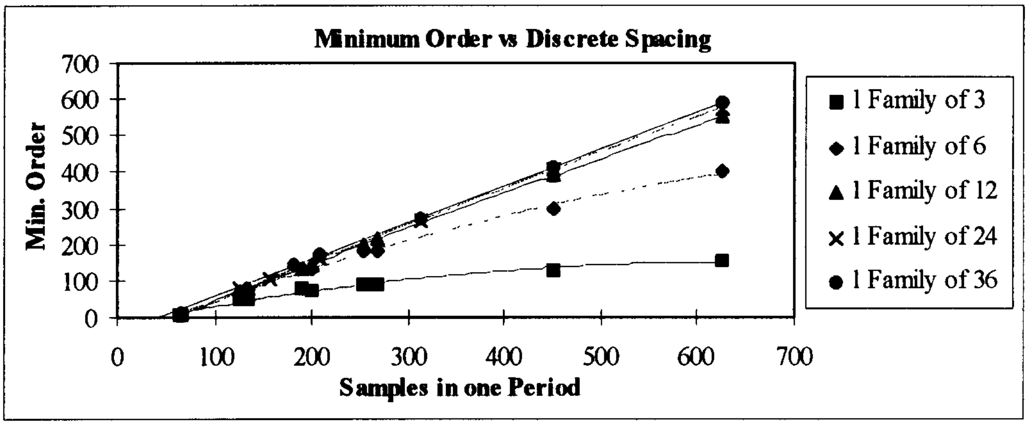

Figure 5- Minimum order vs period of gear components

The first case is where there is only one discrete component. For this case the minimum order should be at least a quarter of the period of the single frequency component. With enough coefficients to form a quarter of the period of the input signals at any time, the coefficients can adapt to shift the phase to equal that of the primary input.

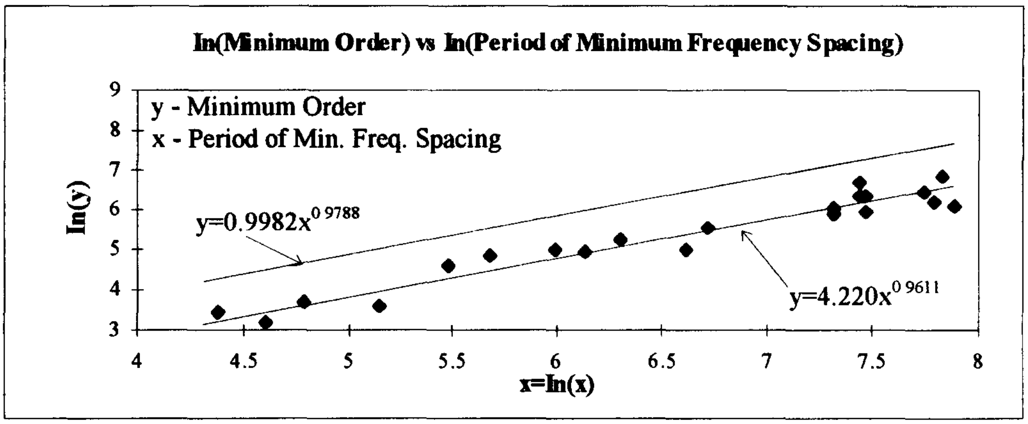

Figure 6- Minimum order vs lowest frequency of randomly spaced gear components

The next case is where there is only one family of discrete components. Here, the two factors determining the minimum order are the spacing and number of the discrete components. Figure 4 shows how the minimum order varies with the number of discrete components at different frequency spacings for typical combinations encountered in a helicopter gearbox. Figure 5 is another plot of the information used in figure 4. It shows how the minimum order varies with the discrete frequency spacings for different numbers of discrete components. It seems that a higher order is required for a larger number of discrete components (up to a certain limit) and a longer period corresponding to the frequency spacing. For a number of discrete components below 12, the relationship is non-linear but for 12 discrete components and higher, the order is approximately equal to the period of the frequency spacing. It must be pointed out that the relationship beyond 12 discrete components is not truly linear, but in fact asymptotes out to a very high value. However since the typical gear frequency which would interfere with the bearing components is unlikely to be above 700 samples per period, the performance curve of the adaptive canceller outside this region is irrelevant and thus was not investigated.

The third way in which the discrete components can be arranged is with random spacings. Figure 6 shows the natural log of the minimum order plotted against the natural log of the period corresponding to the minimum discrete frequency spacing. The graph indicates that an increase in the period of the minimum discrete frequency spacing will require a higher order for the cancellation. The bottom line is the result of linear regression performed on the minimum orders. The top line is recommended for practical purposes as it is obtained from linear regression of orders three times higher than the minimum values.

From figure 4 and figure 6 the minimum order for removing one family of discrete components is higher than the same number of components randomly spaced in the spectrum. This means that the worst situation is one family of components with a very small discrete spacing.

6. CONVERGENCE FACTOR

The relationship between order and convergence factor is shown in figure 7. This graph is obtained by plotting the optimal normalized convergence factor (μ_n) against the order of the FIR filter for all the executions which were successful in removing the discrete components. As μ_n is increased above the optimal value, the steady state error of the adaptive process increases until the μ_n is at such a value that causes it to be unstable.

A linear regression line can be drawn through all the data points and such a linear relationship in a log-log graph indicates the order is a power law function of the convergence factor. However in order to ensure the adaptive process is given the best possibility to converge with the minimum steady state error, values for mu should be chosen from the line 10 times lower than the original regression line (ie the bottom line in figure 7). Due to the reduced convergence rate, extra executions may be performed to allow the adaptation process to settle by using the last set of FIR coefficients for the next execution.

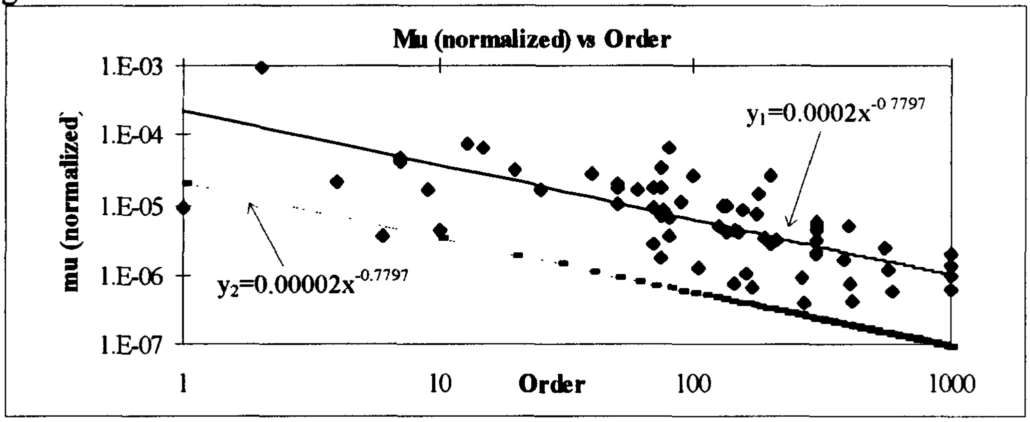

Figure 7- Normalized convergence factor vs order

7. CONCLUSION

When using SANC for bearing fault diagnostics in typical helicopter gearboxes, the time delay should be larger than the correlation time for which the autocorrelation of the bearing signal becomes constant. If there is a single family of discrete frequency components, the choice of the minimum order of the FIR filter should follow the graphs shown in figure 5 and figure 6. If the discrete frequencies are randomly spaced, figure 6 can be used instead. An order 3 times larger than the minimum is recommended for actual application. The normalized convergence factor is a power law function of the order of the FIR filter order and an appropriate value for this variable can be chosen from figure 7.

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