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FM Multipath Noise Reduction

• Kazuo Takayama • Shuji Sugahara • Osamu Tanaka

While receiving an FM broadcast in a moving car, unpleasant noise called "multipath noise" is sometime heard. This noise is produced when the broadcast waves reflected off a building or mountain interfere with those arriving directly. It sounds like "ZAC-ZAC." In order to provide a more stable and higher quality sound, FUJITSU TEN has made great efforts to eliminate such noise. Currently, we have established a multipath noise reduction system far more advanced than conventionally used, and the development of ICs has made it possible to commercialize this system. This system allows adaptive processing by varying the characteristics of noise reduction according to the audio frequency components of broadcast waves: it reduces the deterioration of sound quality, thereby producing a substantial noise eliminating effect. This paper reports the analysis of multipath interference, and the fundamental principle and effect of this new system.

1. Introduction

Car audio components require the performance characteristics of car loading because they are used in a moving vehicle, unlike home audio components. A most difficult problem is a stable and high quality reception against the FM multipath noise generated when receiving an FM broadcast in a moving vehicle. The multipath noise is caused by the phase distortion and amplitude distortion generated when the broadcast waves reflected off a building, mountain, or car interfere with those arriving directly. An unpleasant noise that sounds like "ZAC-ZAC" or a rustling is heard intermittently while the vehicle is in motion.

Noise reduction is most important for car FM tuners, and we have performed various types of research and development. However, the noise is difficult to reduce completely by using present technology. Thus, we also investigated our own system that reduces the noise. We have developed a more effective multipath noise reduction circuit than before and have confirmed its effectiveness.

2. Analysis of multipath interference

A representation of receiving conditions of radio waves is shown in Figure 1. As for the waves from

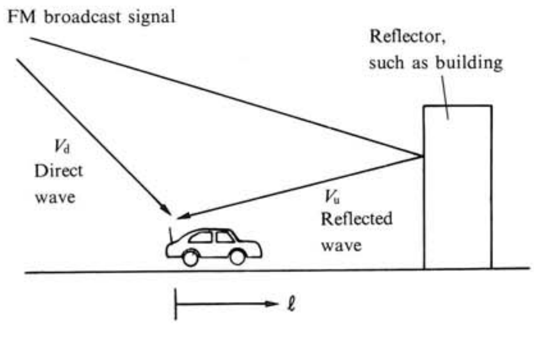

Figure 1. Multipath occurrence conditions

the broadcasting station, direct waves Vd and reflected waves Vu from a building are received by the car's antenna. The phase difference between Vu and Vd, and the amplitude of the resultant signal when a car moves a distance ℓ are shown in Figure 2. The amplitude of the resultant signal reaches a peak when Vu and Vd are in phase (shown by moving distance a), and when they are in the opposite phase (shown by moving distance b), the resultant signal dips. At this point, the resultant signal level may fall

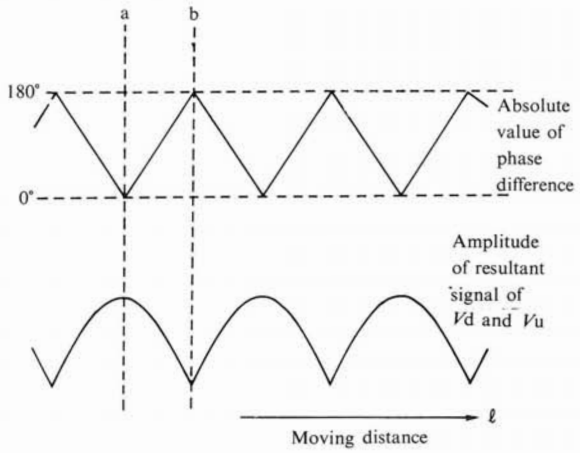

Figure 2. Phase difference and amplitude for moving distance

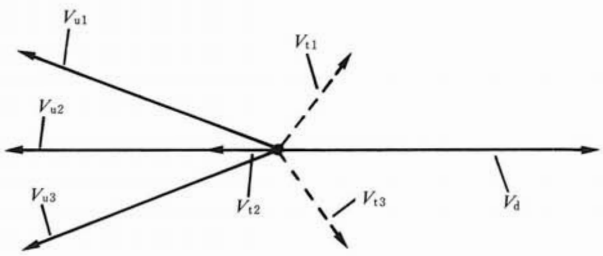

Figure 3. Vector diagram when two FM modulated waves are mixed

below the tuner receiving sensitivity, thus disabling reception. This phenomenon is called "fadeout." At this point, however, even when the resultant signal is more than the tuner receiving sensitivity, "ZAC-ZAC" noise may occur. When Vd and Vu are mixed near the opposite phase, a large phase distortion is generated because Vd and Vu are FM modulated waves and the delay is different between Vd and Vu. Figure 3 shows a vector diagram when the amplitudes of Vu and Vd get closer. Assuming Vu to be Vu_1 at a given moment (t_1), Vu_2 at $\triangle t$ later (t_2), and Vu_3 at $2\triangle t$ later (t_3), the resultant signal varies from Vt_1 to Vt_2, then to Vt_3.

Here, the vector length shows the amplitude, and the angle difference for Vd shows that phase difference, and the resultant signal steeply varies its phase angle and amplitude. Therefore, the resultant signal has amplitude distortion and phase distortion. The amplitude distortion is eliminated by the limiter action of the tuner, but the phase distortion is not eliminated, producing noise and distortion in the demodulated audio signal. This phase distortion is analyzed quantitatively as follows.

As elements to determine multipath, the following is taken into account:

(1) Delay of reflected wave referred to direct wave: τ
(2) DU ratio: $\gamma = V\text{u}/V\text{d}$
(Direct wave amplitude: Vd, Reflected wave amplitude: Vu)
(3) Phase difference: θ
(4) Modulation signal angular frequency: p
(5) Frequency deviation caused by modulation: $\triangle f$
(6) Carrier frequency: f_c

Here, the phase difference is found by

$$\theta = 2\pi\tau(f_c + \triangle f \cos pt) \tag{1}$$

Therefore, the amplitude Vt of the resultant signal is found by

$$V\text{t} = V\text{d}\sqrt{1 + \gamma^2 + 2\gamma\cos\theta} \tag{2}$$

FM demodulator output Vdet for the resultant signal is

$$V\text{det} = 2\pi\triangle f \cos pt + \frac{\gamma^2 + \gamma\cos\theta}{1 + \gamma^2 + 2\gamma\cos\theta} \times 2\pi\triangle f p\tau \cos p(t - \tau/2) \tag{3}$$

When multipath occurs, the calculation results of the demodulate waveform in which the modulation signal is two sine waves with different frequency

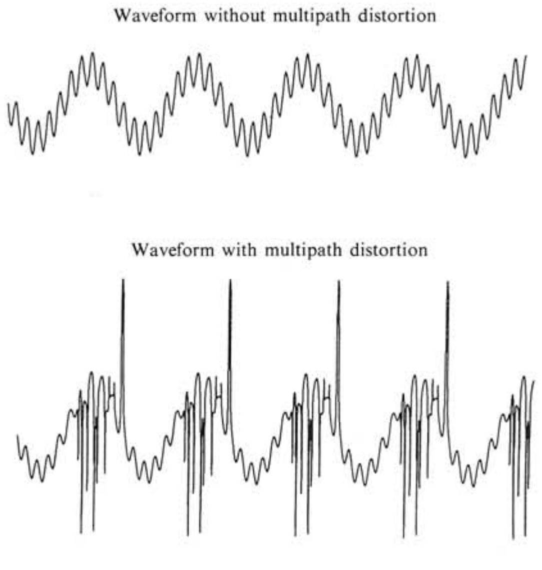

Figure 4. Demodulated waveform when multipath occurs – calculated result

are shown in Figure 4, according to equations (1) and (3).

This waveform corresponds to the conditions in which a car stops in the multipath reception position. Thus, noise and distortion are taking place intermittently. In this paper, noise and distortion are hereafter called simply noise. This noise is distributed at a higher level in a high frequency for a composite signal after FM demodulation, and stereo reception is more vulnerable to the influence of multipath noise than monaural reception, in that a wide frequency range is used.

3. Conventional multipath improvement system

The multipath noise reduction system of car audio manufacturers is basically divided into the following two systems: one is the diversity reception system and the other system detects the multipath noise and controls stereo separation (sometimes together with tone control). We also use this system, and we called it multipath detect automatic separation control (M-ASC). The outline of the system is explained below.

3.1 M-ASC

FM tuners perform stereo reception if the field strength is high enough. Since the FM tuner is easily influenced by multipath noise during stereo reception, the M-ASC detects multipath noise and automatically reduces stereo separation (makes the reception monaural).

If the stereo separation is changed frequently, the sound is heard as if it were swinging. To prevent this, the time constant to reduce the stereo separation is shortened and the time constant to recover the stereo separation is prolonged.

The bounds of M-ASC improvement are explained below. The FM broadcast wave modulation spectrum consists of an L+R signal, a pilot signal, and an L−R signal. For monaural reception, only the L+R signal is demodulated. Multipath noise is mostly distributed in the higher frequency range. The M-ASC can eliminate the noise in the L−R channel (stereo signal), but it cannot eliminate the noise in the L+R channel (monaural signal).

3.2 Diversity reception system

The diversity reception system, using multiple antennas, improves the reception by reducing intermittent multipath noise. When the multipath noise is detected, the receiving antenna is switched to another antenna at which the received signal is not affected by multipath interference. This results in better reception.

In general, the diversity reception system can reduce the multipath noise generation time and frequency by about 70 to 90%. When the multipath noise is generated from both antennas, the receiving state is not improved. The multipath noise irritates the ear even when the multipath noise duration is short.

4. New multipath noise reduction system

4.1 Main point of new system

One system for eliminating multipath noise employed in the past used a method of detecting generation of multipath noise, and reducing the stereo separation. In that case, noise in the stereo differential signal (L−R) channel is eliminated, while noise in the sum signal (L+R) channel remains. In a newly developed multipath noise reduction system, however, processing in the audio stage makes it possible to eliminate noise in this sum signal channel. For this processing in the audio

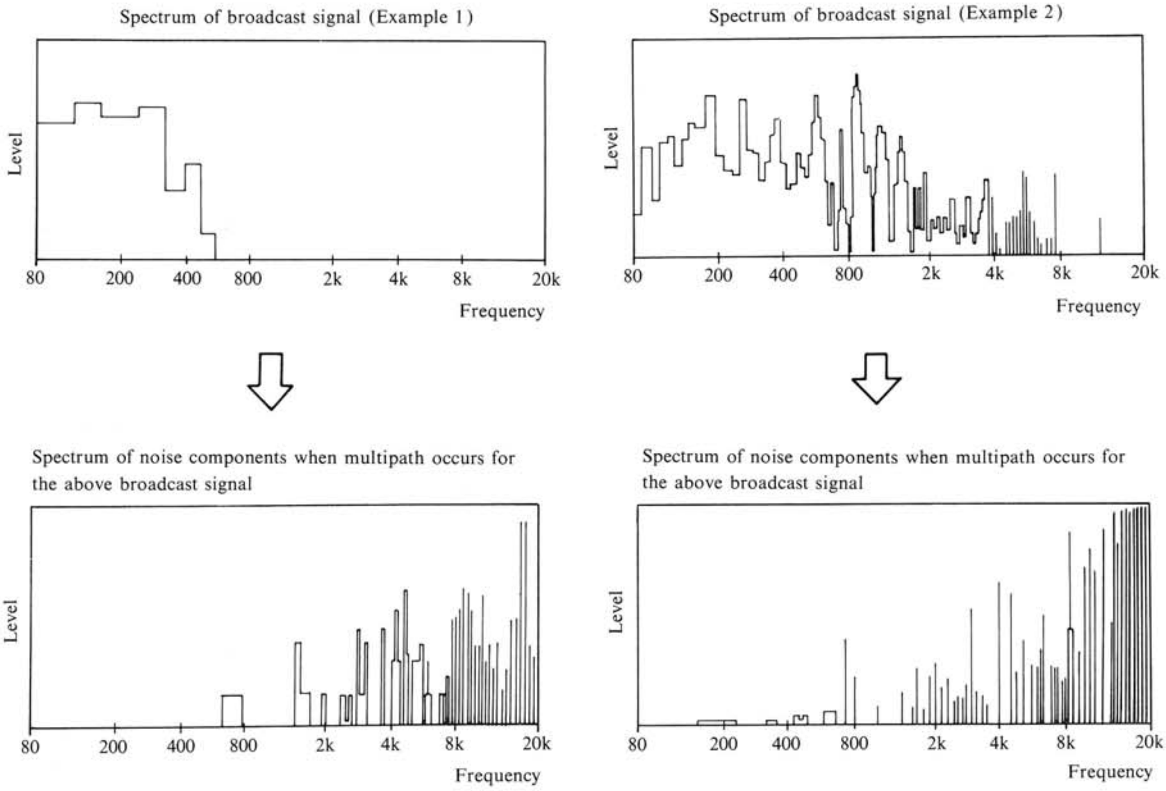

Figure 5. Spectrum when multipath occurs — actual broadcast

stage, due attention should be paid to the characteristics of multipath noise in the audio stage, and the characteristics of voice and music. The status when multipath noise was produced in actual broadcast waves is shown in Figure 5. Here are two examples in which the voice contents of broadcasting waves are different between the right figure and left figure. On the upper figures, the spectrum of broadcast waves (no multipath is generated) is shown, while the noise spectrum when multipath is generated is shown on the lower figure. Thus, it is found that noise caused by multipath is mostly present in higher frequency ranges.

From the above items, the aforementioned theoretical analysis and past experimental facts, the following can be said.

(1) Even when weighted multipath noise continues, there are times which produce a lot of noise in particular and times which are less affected by noise.
(Noise taking place intermittently.)

(2) More multipath noise is present in high frequency ranges.

(3) The spectrum of voice and music signals may be concentrated in the low frequency range in some periods, and it may distribute to high frequency range in other periods.

(4) Due to the characteristics of human hearing, for audio signals with few high-frequency components, high-frequency noise is apt to be irritating to the ear, whereas for signal with more high-frequency components, high-frequency noise

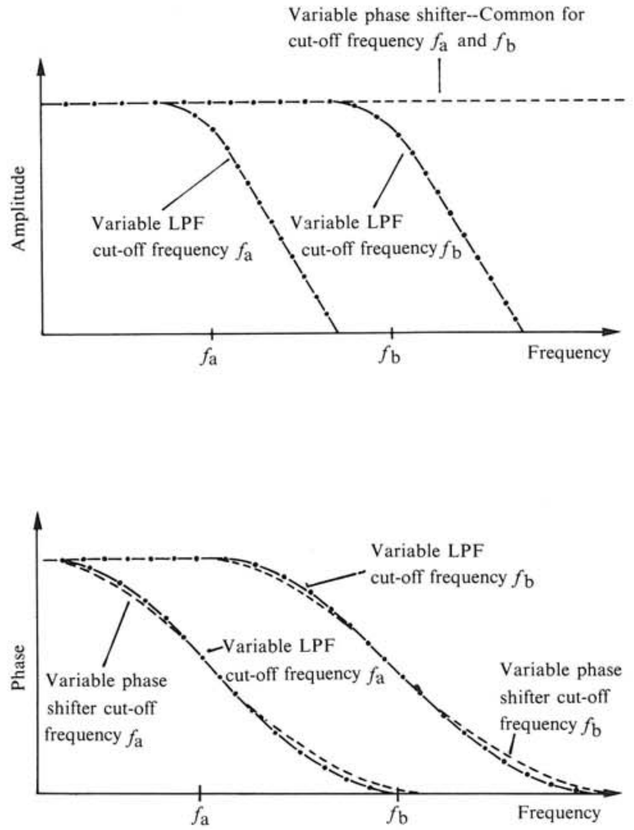

Figure 6. Characteristics of variable LPF and variable phase shifter

becomes unnoticeable due to masking effect.

(5) The spectrum distribution of broadcast audio signal are considered to be constant for a short period of time.

4.2 Outline of new system

Based on the aforementioned characteristics, we planned to develop a new multipath noise reduction system, which is discussed below. From the aforementioned characteristics (1), to reduce multipath noise, all that must be done is to detect periods of the signal with more noise, and reduce the noise in the periods. From characteristics (2), the noise reduction effect is produced by filtering the signal with a low-pass filter (LPF). When the signal is filtered with this LPF, sound quality is degraded, but by addressing characteristics (3) and (4), changes in sound quality are avoided by varying LPF cut-off frequency according to the frequency components in the input signal. The LPF cut-off frequency control operates even in multipath noise, by addressing characteristics (5), the LPF cut-off frequency should be set to a value before multipath noise is generated.

Consequently, this new system determines the cut-off frequency of the noise reduction filter (LPF) according to the signal components before a multipath signal is generated, thereby filtering the noisy periods. Following is the explanation of its details.

4.3 Operation of new system

Noise can be reduced by filtering the signal with the LPF, but at the same time, signal components higher than the LPF cut-off frequency are also impaired. Consequently, the time in which signal is filtered with the LPF should be reduced to the minimum required. Even noise which sounds continuous to the ear is produced intermittently as aforementioned, and this noisy period only may be filtered. However, if signals are intermittently filtered with the LPF, wave distortion will occur. This is because phase shift is generated by the LPF. To avoid such wave distortion, a phase shifter having the same phase characteristics as the LPF is provided, and switching is done between the phase shifter and LPF outputs. The LPF and phase shifter vary according to the frequency components of input signal, which are hereafter called variable LPF and variable phase shifter.

Figure 6 shows the amplitude and phase characteristics when the variable LPF cut-off frequency is f_a and f_b together with the characteristics of the variable phase shifter.

Figure 7 shows the block diagram of the noise reduction filter. Figure 8 shows the operation timing chart. Here, (a) to (e) show the waveforms at the respective points in Figure 7. In input signal (a), some high frequency components are superimposed on low frequency components, which shows that intermittent noise is added. Variable LPF output at point (b) is reduced in noise, and at the same time, high frequency components are impaired. Variable phase shifter output at point (c) is the same as input in noise level, but the signal phase coincides with (b). For output (d), when no multipath noise is

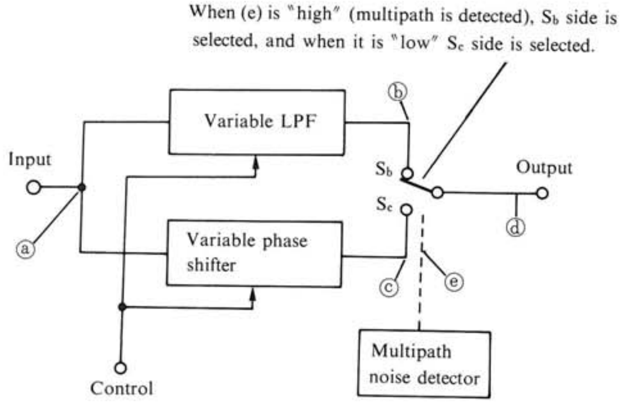

Figure 7. Block diagram of noise reduction filter

produced, (c) side (S_c side) is selected, using a switch, and when multipath noise is generated, (b) side (S_b side) is selected. According to such processing, high-frequency components are imparied very little, but noise is greatly eliminated.

Next, the description of the control of variable LPF is given. If the input signal frequency f_{in} is a single frequency, the cut-off frequency of the variable LPF may be approximately f_{in}. Actual broadcast signals contain a number of frequency components, and by regarding frequency components exceeding a certain level as necessary, the variable LPF cut-off frequency is determined.

Figure 9 shows the block diagram including the cut-off frequency control circuit. The variable phase shifter allows a signal in all bands to pass without attenuation, and the amplitude is constant for phase variation, while the variable LPF varies in signal output amplitude for cut-off frequency changes. Therefore, it is preferable to form a feedback loop which controls the variable LPF cut-off frequency so that the variable LPF output and variable phase shifter output coincide with each other in amplitude, except for the error allowable value (ℓ_s). This error allowable value (ℓ_s) should be regulated comprehensively, depending on music and voice characteristics, multipath noise characteristics, and acoustic characteristics. Figure 10 shows the operation chart when the input is a single frequency with f_{in} frequency.

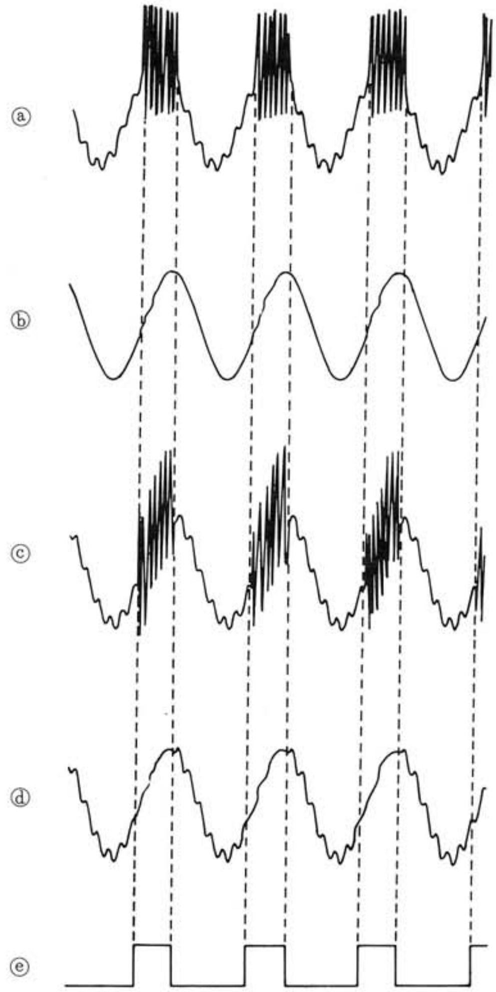

Figure 8. Timing chart of noise reduction

The left figure shows the case in which input frequency f_{in} is lower than the LPF cut-off frequency in initial conditions, while the right one shows the case in which f_{in} is higher than the cut-off frequency in initial conditions. (h) to (k) show the levels of the respective points in Figure 9. The loop filter is an integrator: if (k) value is negative, the loop filter operates in the direction to decrease the LPF cut-off frequency, and if (k) is positive, it operates in the direction to increase the cut-off frequency. When multipath is detected, the integrating action is stopped, thus maintaining the cut-off frequency before multipath noise is generated.

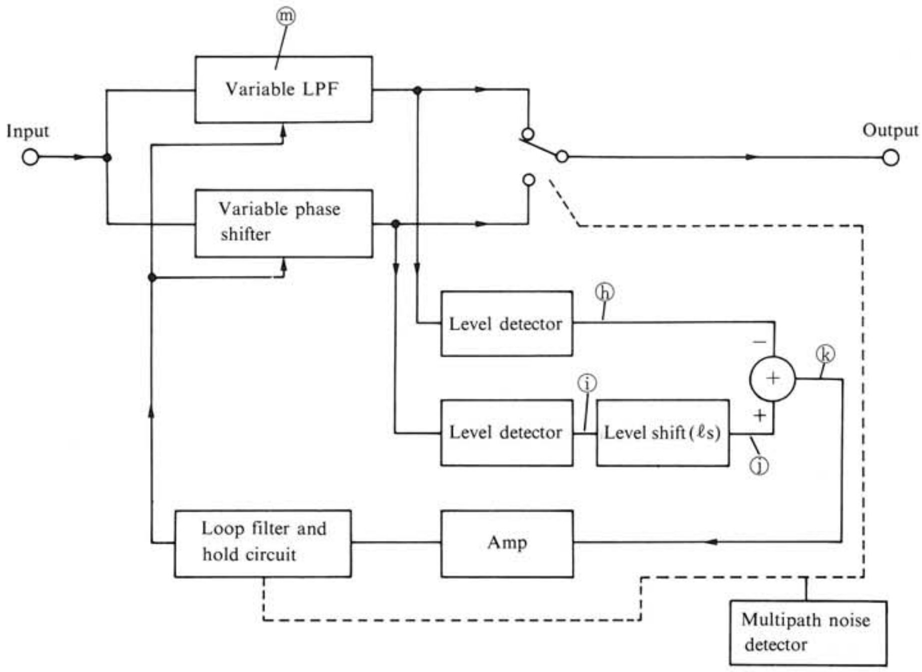

Figure 9. Block diagram of cut-off frequency control

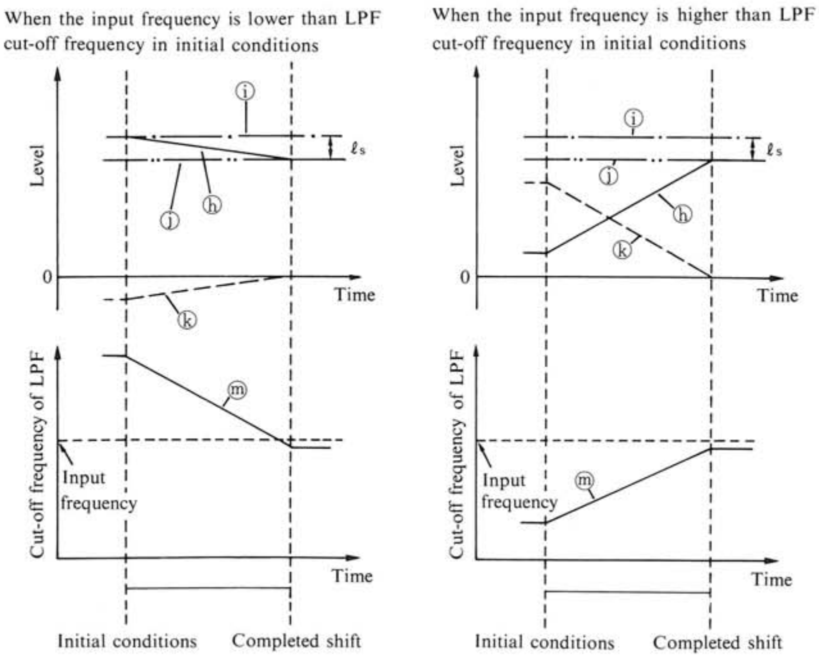

Figure 10. Cut-off frequency control operation chart

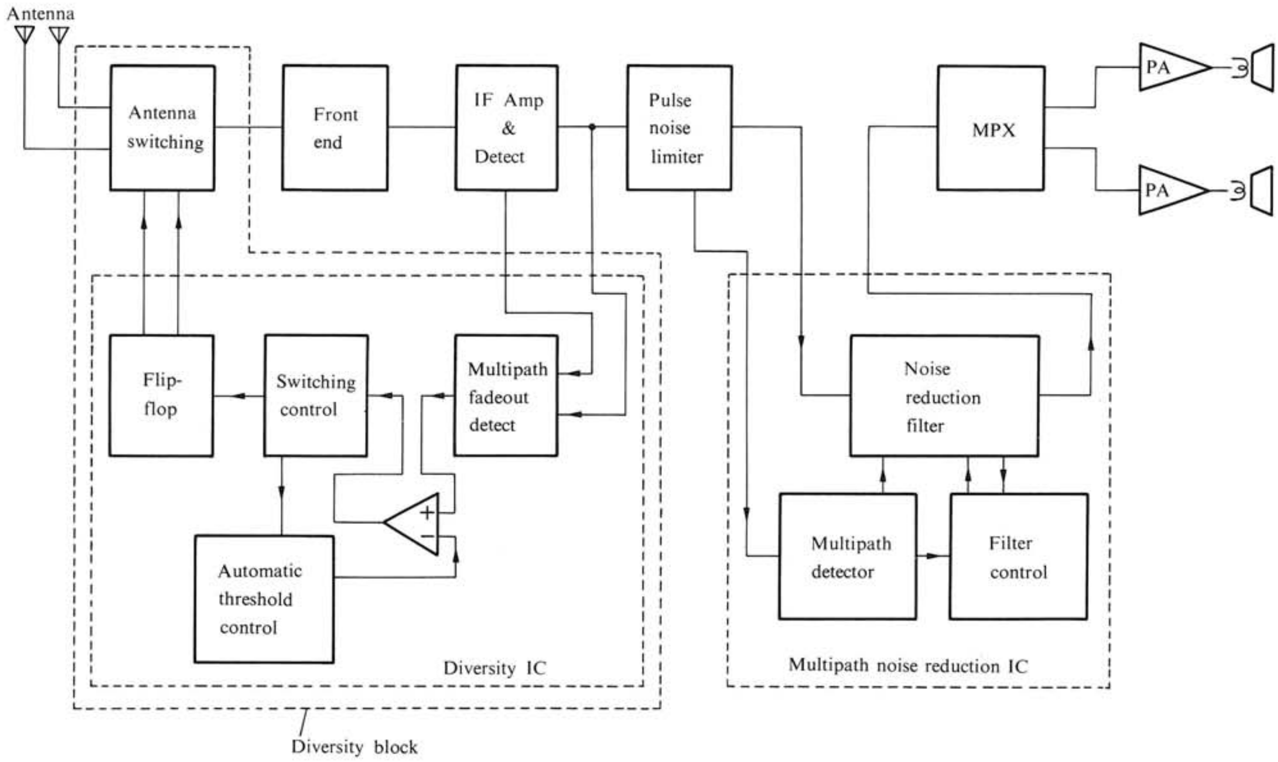

Figure 11. The whole block of tuner with diversity and multipath noise reduction

Next, a brief description of multipath noise detection is given. Multipath noise is detected by monitoring the level the high-pass filter (HPF) output, considering that high-frequency noise is generated when multipath interference occurs. The HPF cut-off frequency is selected higher than L−R so that it is not operated by a normal L+R and L−R signal.

5. Commercialization and effect of multipath noise reduction system

This system can be implemented as configured in Figure 9; however, by assembling with discrete components and general purpose ICs, the system is far from practical both in cost and in size; therefore, this system is put to practical use by developing custom ICs for this system. This multipath noise reduction circuit is more effectively used in combination with diversity system, and FUJITSU TEN has also developed and marketed custom ICs for diversity system. There are two diversity systems: one is a selection system which continuously compares the receiving conditions of the receiving systems prepared for each antenna and selects the best one, and the other is a scanning system in which a switching circuit at the input of a single receiving system transfers to the next antenna when a multipath noise detecting signal exceeds a predetermined threshold level. Our diversity system uses the scanning system: this system produces the same improvement and effect as the selective system by modifying the switching threshold level to a variable threshold, varied corresponding to the switching frequency.

Figure 11 shows the block diagram with diversity reception and the multipath noise reduction system combined. Next a description is given of these effects. When a field test is conducted on a combination of both systems on an actual car, it is found that the noise level is improved to such an extent that noise does not distract the listener in a place where the conventional multipath noise would be irritating to the ear.

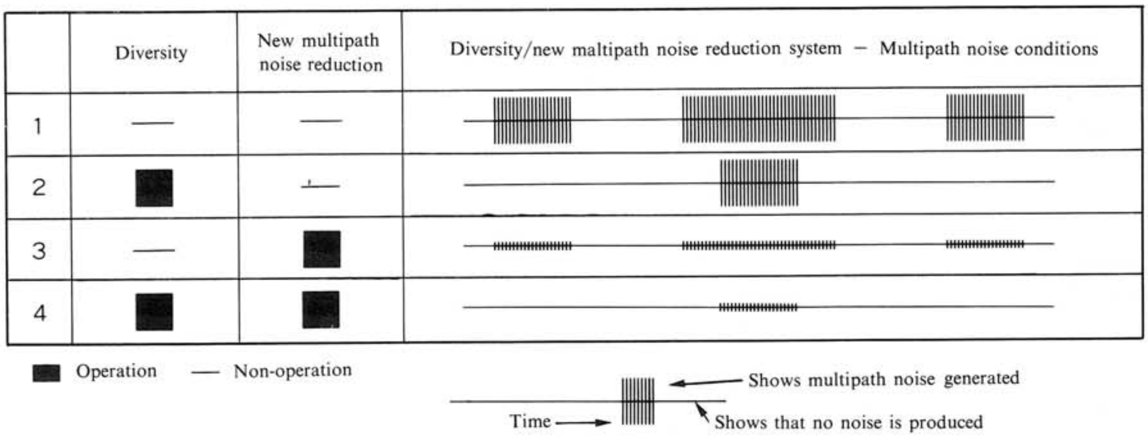

Figure 12. Effect of diversity and new multipath noise reduction system

Figure 12 diagramatically shows the effect of the combined systems. In the diversity system, the multipath noise occurrence frequency and duration are reduced, but the noise level, when noise occurs, remains unchanged. In the multipath noise reduction system, the multipath noise occurrence frequency and duration do not change, but the noise level, when noise occurs, is improved. Therefore, both systems, when combined, improve both noise level and noise occurrence frequency.

6. Conclusion

As previously stated, we developed and marketed a multipath noise reduction system far more advanced than is currently used, by creating an IC containing all of necessary circuit on a single chip. Further noise reduction method studies will be conducted as we encounter more multipath noise generating conditions in the future.

Reference

Kazuo Takayama, Shuji Sugahara, Osamu Tanaka, and Shigeki Fukuya: "FM Multipath Noise Reduction," SAE paper 880089 (1988)

Kazuo Takayama

Entered the company in 1976, where he has been engaged in auto radio circuit and IC R&D. He is currently with the 1st Research and Development Department.

Osamu Tanaka

Entered the company in 1973, where he has been engaged in land-mobile radio R&D, and in radio application device R&D. He is currently with the 1st Research and Development Department.

Shuji Sugahara

Entered the company in 1977, where he has been engaged in auto radio circuit and IC R&D. He is currently with the 1st Research and Development Department.