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Research Report

Noise Suppression System for AM Radio Receiver Using Quadrature Component of Received Signal

Tomohisa Harada, Yoshiyuki Hattori, Shinya Ito, Mitoshi Fujimoto and Toshikazu Hori

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ABSTRACT With the rising popularity of hybrid vehicles (HVs), the electromagnetic noise generated by the power control units (DC-DC converters, inverters), electric power steering (EPS) control modules, and other power electronics devices in these vehicles, has given rise to a serious AM radio receiver interference problem. The conventional solutions for this problem are filtering the noise sources, along with shield wiring and ferrite cores for noise propagation paths. In this paper, we present an electromagnetic noise suppression system for an AM radio using the quadrature component of the received signal. In this system, the AM radio signal being interfered with by electromagnetic noise is quadrature demodulated. A replica of the noise signal is generated, using the noise signal included in the quadrature component. The replica noise signal is then subtracted from the in-phase component that includes the AM radio signal and the electromagnetic noise.

In this paper, we first describe the principle of the noise cancelation method. We then build a prototype AM radio receiver system based on this method. Finally, we demonstrate that the system can suppress the DC-DC converter and EPS noise, simultaneously superimposed on the AM radio signal, by more than 15 dB.

KEYWORDS Noise Suppression, AM Radio, Quadrature Demodulation, DC-DC Converter, Inverter, Electric Power steering (EPS), Hybrid Vehicle (HV)

1. Introduction

Electromagnetic noise (HV noise) generated from power control units (DC-DC converters, inverters), electric power steering (EPS) control modules, and other power electronics devices in hybrid vehicles (HV), gives rise to a serious problem of AM radio reception interference, as shown in **Fig. 1**.[1] To tackle this problem, noise suppression methods at noise sources and propagation paths have been conventionally taken. For example, in the case of noise sources, filters are used, and in the case of propagation paths, shield wiring, ferrite cores, or capacitors are used.[2,3] These methods require a variety of electronic components. A reduction in the number of such noise suppression components is needed.

Recently, noise suppression methods within the radio receiver have been proposed.[4,5] One such approach is shown in **Fig. 2**.[4] The noise signal is received by a sensor located near the power control unit. The noise signal is then subtracted from the AM radio signal being interfered with by the HV noise. This method requires a noise sensor, which needs to be carefully located so that it only detects the target noise; a sufficient noise suppressing effect can only be obtained when the target noise is accurately detected. It is also necessary to shield the cable that connects the signal processing circuit with the radio antenna, to prevent interference from other signals.

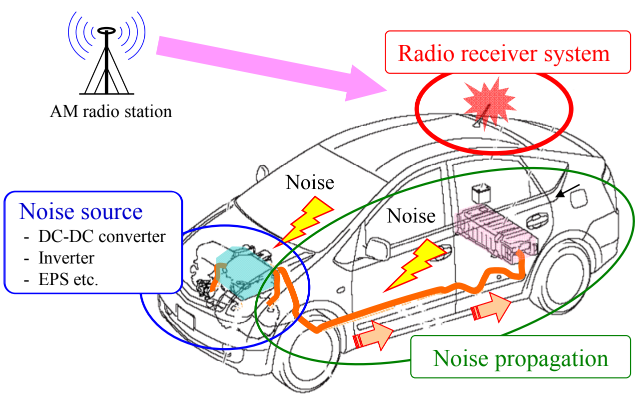


Fig. 1 Electromagnetic interference to receiver system caused by HV noise.

Alternatively, a method that utilizes the periodicity of HV noise has been proposed.[5] This method cancels the noise by using the correlation between the noise in the frequency band at which no radio signal exists and the noise superimposed on the radio signal.[5] However, the suppression performance deteriorates drastically when the periodicity of the noise changes even slightly. In addition, it is difficult to simultaneously cancel noise from multiple sources.

We propose a new noise suppression method using digital signal processing in the AM radio receiver.[6,7] This method needs neither a noise sensor nor periodicity of the HV noise. Instead, a received AM radio signal, interfered with by HV noise, is resolved by quadrature demodulation into an in-phase component and a quadrature component of the carrier. As a result, the AM radio signal and the HV noise appear in the in-phase component, and only the HV noise appears in the quadrature component. The HV noise interfering with the AM radio signal is canceled by using the noise in the quadrature component.

In this paper, we briefly describe quadrature demodulation of an AM radio signal being interfered with by HV noise. We then describe the principle of noise cancelation using the noise in the quadrature component. Finally, we build a prototype of the AM radio receiver system and demonstrate that the system can suppress DC-DC converter and EPS noise, simultaneously superimposed on the AM radio signal, by more than 15 dB.

2. Quadrature Demodulation of AM Radio Signal Containing HV Noise

The principle of quadrature demodulation of an AM radio signal being interfered with by HV noise is shown in **Figs. 3** and **4**. The AM radio signal is generated by varying the amplitude of the carrier signal in accordance with the audio signal $a(t)$, as shown in Fig. 4(a). Thus, the phase of the AM radio signal is always equal to that of the carrier. This means that the AM radio signal only has a component that is in phase with the carrier.

Figure 3 shows a block diagram of the quadrature demodulation process. The received signal $r(t)$ is multiplied by two sinusoidal signals, denoted by the in-phase carrier and the quadrature carrier. The frequencies of these signals are equal to the carrier frequency, but the phases are different by 90 ° to each other. Low-frequency components are extracted by low-pass filtering. The signals obtained by multiplying the in-phase carrier and the quadrature carrier are called the in-phase component and the quadrature component, respectively. The AM radio signal $r_{AM}(t)$ can be expressed as

$$r_{AM}(t) = a(t)\cos\omega_c t \,, \tag{1}$$

where $a(t)$ and ω_c denote the audio signal and the carrier frequency of AM radio, respectively. Hence, the in-phase component and the quadrature component of the AM radio signal are obtained using

$$\begin{aligned} i_{AM}(t) &= LPF\left[r_{AM}(t)\cos\omega_c t\right] \\ &= a(t), \end{aligned} \tag{2}$$

$$\begin{aligned} q_{AM}(t) &= LPF\left[r(t)\cos(\omega_c t + \pi/2)\right] \\ &= 0, \end{aligned} \tag{3}$$

where LPF[*] denotes the low-pass filtering process. As shown in Eqs. (2) and (3), only the audio signal $a(t)$ appears in the in-phase component $i_{AM}(t)$, and no signal appears in the quadrature component $q_{AM}(t)$. The time waveforms are shown in the center of Fig. 4(a). The Fourier transform of these components can be written as

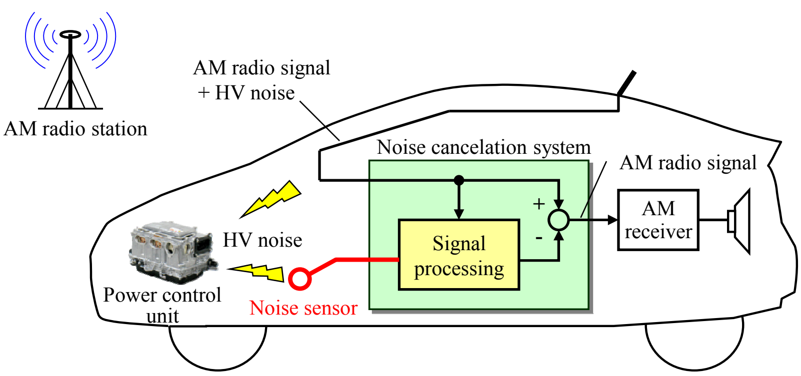


Fig. 2 Noise cancelation system using noise sensor.

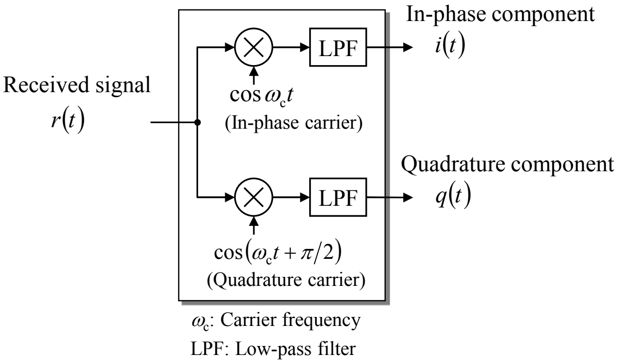


Fig. 3 Block diagram of the quadrature demodulation.

$$I_{\mathrm{AM}}(\omega) = A(\omega), \tag{4}$$

$$Q_{\mathrm{AM}}(\omega) = 0, \tag{5}$$

where $A(\omega)$ denotes the Fourier transform of $a(t)$. The frequency spectra of these two components are shown on the right side of Fig. 4(a). The carrier signal, the upper side band (USB) and the lower side band (LSB), which are the components of the AM radio signal, appear in the in-phase component. In contrast, no signal appears in the quadrature component.

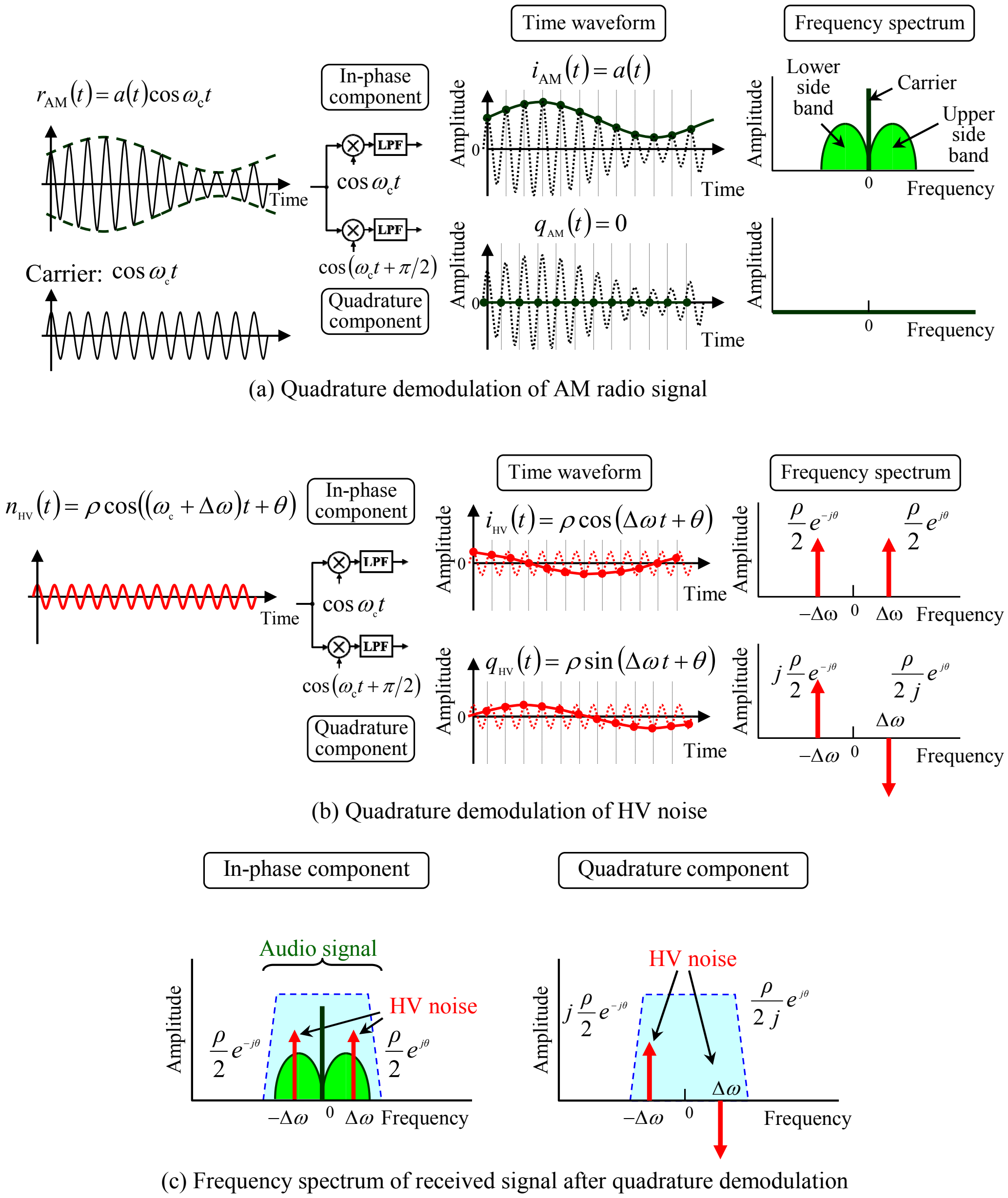


Fig. 4 Quadrature demodulation of received signal.

We now consider quadrature demodulation of the HV noise. HV noise generated by sources such as the DC-DC converter and the inverter is composed of a number of sinusoidal signals. Because HV noise is generally asynchronous with the carrier, its frequency and phase do not coincide with those of the carrier. The HV noise signal $n_{\mathrm{HV}}(t)$, which is mixed in the receiver channel, can be expressed as

$$n_{\mathrm{HV}}(t) = \rho\cos((\omega_{\mathrm{c}} + \Delta\omega)t + \theta) \text{ ,} \tag{6}$$

where ρ and θ denote the amplitude and the phase of HV noise, respectively, and $\Delta\omega$ denotes the frequency difference between the carrier and the HV noise. Hence, the in-phase component and the quadrature component of the HV noise are obtained as shown below.

$$\begin{aligned} i_{\mathrm{HV}}(t) &= LPF[n_{\mathrm{HV}}(t)\cos\omega_{\mathrm{c}}t] \\ &= \rho\cos(\Delta\omega t + \theta) \end{aligned} \tag{7}$$

$$\begin{aligned} q_{\mathrm{HV}}(t) &= LPF[n_{\mathrm{HV}}(t)\cos(\omega_{\mathrm{c}}t + \pi/2)] \\ &= \rho\sin(\Delta\omega t + \theta) \end{aligned} \tag{8}$$

As shown in Eqs. (7) and (8), the noise signal whose frequency is equal to the frequency difference $\Delta\omega$ between the carrier and the HV noise appears in both components. The time waveforms are shown in the center of Fig. 4(b). The Fourier transform of these components can be written as

$$I_{\mathrm{HV}}(\omega) = \frac{\rho}{2}e^{j\theta}\,\delta(\omega - \Delta\omega) + \frac{\rho}{2}e^{-j\theta}\,\delta(\omega + \Delta\omega), \tag{9}$$

$$\begin{aligned} Q_{\mathrm{HV}}(\omega) = &\frac{\rho}{2j}e^{j\theta}\,\delta(\omega - \Delta\omega) \\ &+ j\frac{\rho}{2}e^{-j\theta}\,\delta(\omega + \Delta\omega), \end{aligned} \tag{10}$$

where $\delta(\omega)$ denotes the Dirac delta function. By comparing the corresponding frequency terms in Eqs. (9) and (10), their amplitudes are found to be equal to $\rho/2$, and the phase difference between the components is 90°. The frequency spectra of these components are shown on the right side of Fig. 4(b).

The frequency spectra of the in-phase component and the quadrature component of the quadrature-demodulated signal, which includes both the AM signal and the HV noise, are shown in Fig. 4(c). The components are obtained by adding the corresponding components in Figs. 4(a) and (b). The Fourier transform of the two components can be expressed as follows:

$$\begin{aligned} I(\omega) = &A(\omega) + \frac{\rho}{2}e^{j\theta}\,\delta(\omega - \Delta\omega) \\ &+ \frac{\rho}{2}e^{-j\theta}\,\delta(\omega + \Delta\omega), \end{aligned} \tag{11}$$

$$Q(\omega) = \frac{\rho}{2j}e^{j\theta}\,\delta(\omega - \Delta\omega) + j\frac{\rho}{2}e^{-j\theta}\,\delta(\omega + \Delta\omega). \tag{12}$$

As shown in Fig. 4(c), both the audio signal and the HV noise appear in the in-phase component. In contrast, only the HV noise appears in the quadrature component.

3. Proposed HV Noise Cancelation Method by Using Quadrature Demodulation

Figure 5 shows the principle of the proposed HV noise cancelation method. As an example, the cancelation procedure is described for the case of HV noise interfering with the USB of the AM radio signal. As shown by Eqs. (11) and (12), the noise signal of frequency $\Delta\omega$ in the quadrature component is delayed by 90° compared to the noise signal of the corresponding frequency in the in-phase component. On the other hand, the noise signal of frequency $-\Delta\omega$ in the quadrature component is ahead by 90° compared to the noise signal of the corresponding frequency in the in-phase component. Therefore, in the proposed method, the phase of the noise signal of frequency $\Delta\omega$ in the quadrature component is shifted by +90°, and the phase of the noise signal of frequency $-\Delta\omega$ in the quadrature component is shifted by −90°. It follows that a replica of the noise signal contained in the in-phase component can be generated. In the case of the HV noise interfering with the LSB of the AM radio signal, the direction of the phase shift is reversed. Finally, the HV noise can be canceled by subtracting the replica noise from the in-phase component that includes the AM radio signal and the HV noise.

Figure 6 illustrates the structure of the noise cancelation block shown in Fig. 5. First, the in-phase and quadrature components are transformed from the time domain into the frequency domain using a fast Fourier transform (FFT). The noise cancelation procedure is executed in the frequency domain. As stated above, the direction of the noise phase shift depends on whether the noise interferes with the USB or the LSB while generating the replica of the noise. In the proposed method, the noise phase shift direction is determined on the basis of the complex correlation between the in-phase and quadrature components. The complex correlation in the frequency domain is calculated using

$$R_{\mathrm{IQ}}(\omega) = MA\left[I(\omega)Q^{*}(\omega)\right] \approx j\left(\frac{\rho}{2}\right)^{2}\delta(\omega-\Delta\omega) - j\left(\frac{\rho}{2}\right)^{2}\delta(\omega+\Delta\omega), \quad (13)$$

where MA[*] denotes the moving average. From Eq. (13), the complex correlation at the noise frequency is given by

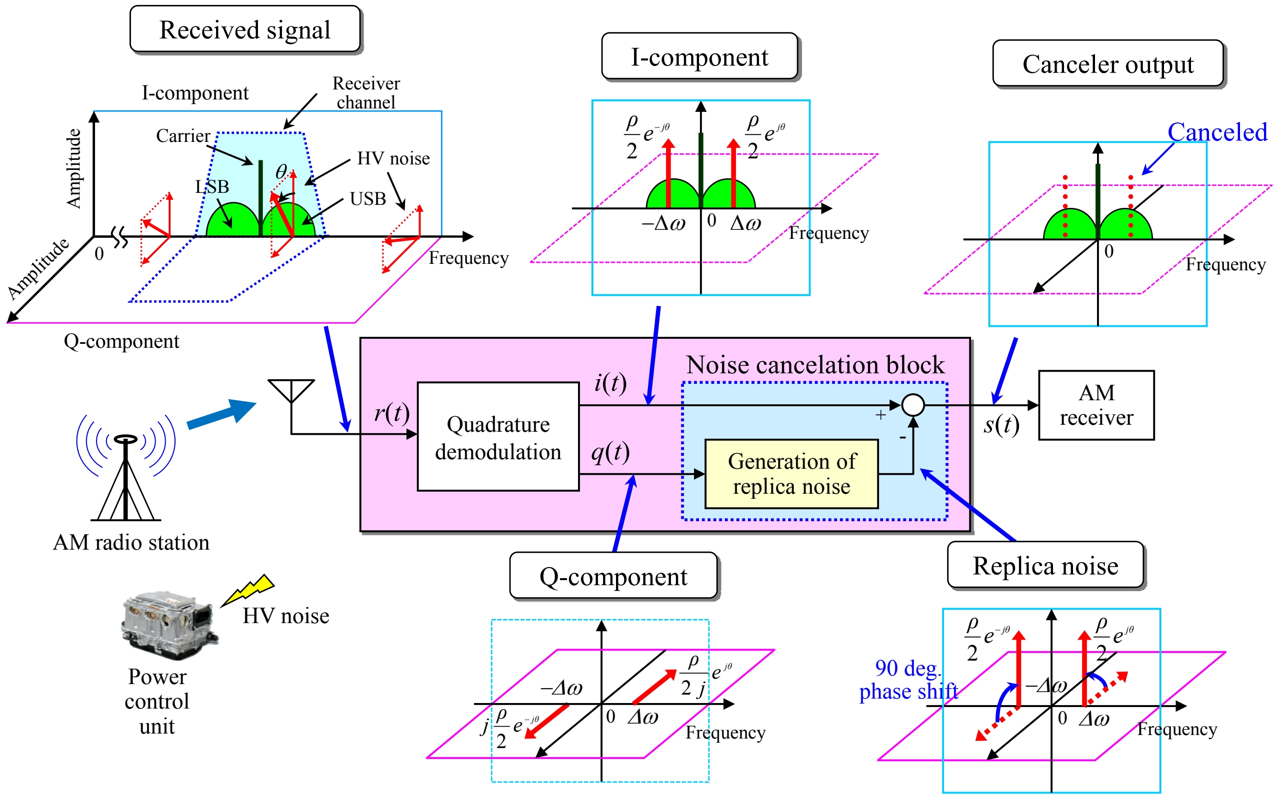


Fig. 5 Principle of proposed HV noise cancelation method.

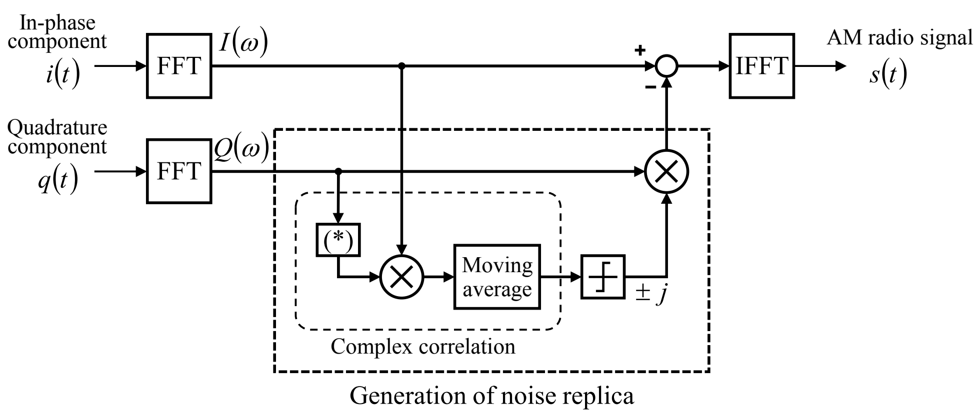


Fig. 6 Structure of HV noise cancelation block.

$$R_{IQ}(\Delta\omega) \approx j\left(\frac{\rho}{2}\right)^2 > j0\,, \tag{14}$$

$$R_{IQ}(-\Delta\omega) \approx -j\left(\frac{\rho}{2}\right)^2 < j0\,. \tag{15}$$

In the noise cancelation block, the phase of the noise element in the quadrature component, whose correlation value is positive imaginary, is shifted by +90° by multiplying the noise element by j. In contrast, the phase of the noise element in the quadrature component, whose correlation value is negative imaginary, is shifted by −90° by multiplying the noise element by $-j$. As a result, the replica of the noise signal is given by

$$\begin{aligned} N_{\mathrm{Rep}}(\omega) &= j \times \frac{\rho}{2j} e^{j\theta}\,\delta(\omega - \Delta\omega) + (-j) \\ &\quad \times j\frac{\rho}{2} e^{-j\theta}\,\delta(\omega + \Delta\omega) \\ &= \frac{\rho}{2} e^{j\theta}\,\delta(\omega - \Delta\omega) + \frac{\rho}{2} e^{-j\theta}\,\delta(\omega + \Delta\omega). \end{aligned} \tag{16}$$

Subtracting the replica noise from the in-phase component, and transforming the in-phase component from the frequency domain to the time domain using an inverse FFT (IFFT), the AM radio signal from which the HV noise is removed is output.

As described above, the proposed method has the following advantages. (1) A noise sensor is not necessary, because noise cancelation can be achieved using only the received signal. (2) The performance of noise suppression is not affected by the sensing accuracy of the noise, because the replica noise is generated from the received signal. (3) The proposed method is applicable for cancelation of noise from a number of sources, because periodicity of the noise is not assumed.

4. Prototyping of AM Radio Receiver with Proposed Method

In order to experimentally verify the effect of the proposed cancelation method, we built a prototype of an AM radio receiver using GNU Radio and the Universal Software Radio Peripheral (USRP).[8,9] Here, GNU Radio refers to a free and open-source software development toolkit that provides signal processing blocks to implement software radios. GNU Radio Companion (GRC) is a graphical tool of GNU Radio for creating signal flow graphs and generating flow graph source code.[8] The USRP is a software radio platform for designing and evaluating wireless communication systems. **Figure 7** shows the configuration of the prototype receiver system. The received signal is amplified and filtered to remove the noise from the AM radio band in the receiver front end, and converted to a digitized complex intermediate frequency (IF) signal in the USRP. Quadrature demodulation, noise cancelation and AM demodulation are then performed in real time on the PC, and an audio signal is output from the PC speaker. **Figure 8** shows the appearance of the prototype receiver system. **Figure 9** shows the signal flow graph created in GRC.

5. Verification of Noise Suppression Effect with Prototype Receiver

The noise suppression effect is verified experimentally for noise generated by two different sources, i.e., the step-down DC-DC converter and the inverter of the EPS control module. **Figure 10** shows the experimental method. The AM signal is generated by a signal generator (SG). Once the AM radio signal,

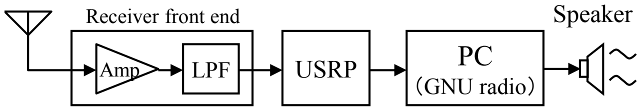


Fig. 7 Configuration of prototype receiver system.

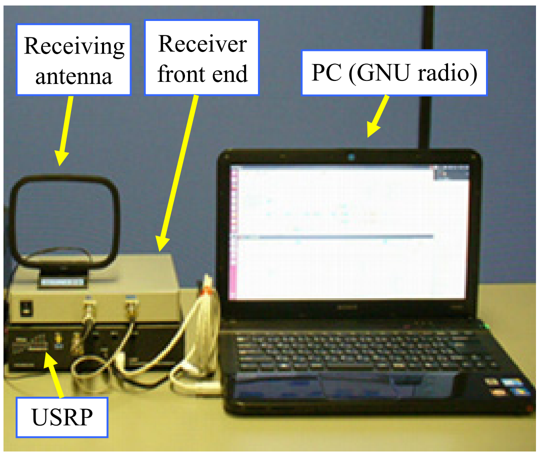


Fig. 8 Photo of prototype receiver system.

the DC-DC converter noise and the EPS noise are separately received and stored, then they are retrieved and summed by the PC to verify the effect of the proposed method.

The frequency band from 531 to 1602 kHz is allocated for AM radio broadcasting in Japan.(10) The operating frequency of the DC-DC converter and the inverter of the EPS are approximately 170 and 20 kHz, respectively. Hence, a number of harmonics interfere with the AM radio band. Since the frequency bandwidth per AM radio channel is 15 kHz, two harmonics, at most, are mixed in an AM radio channel. In the experiment, the carrier frequency of the AM radio signal was adjusted so that the 4th-order harmonics of the DC-DC converter noise and the 34th-order harmonics of the EPS noise were contained in the AM radio band. Here, the frequency difference Δf_1 between the carrier and the DC-DC converter noise was set to 1.5 kHz, and the frequency difference Δf_2 between the carrier and the EPS noise was set to 1.2 kHz, in order to generate a clearly audible tone in the case of insufficient cancelation.

Figure 11 shows the frequency spectra of the received signal and the canceling output in the case that the DC-DC converter noise and the EPS noise interfere with both sidebands of the AM radio. Because the sideband of the AM radio signal varies greatly depending on the audio signal, the frequency spectra for a silent period are shown to clarify the cancelation effect. The superimposed noise is

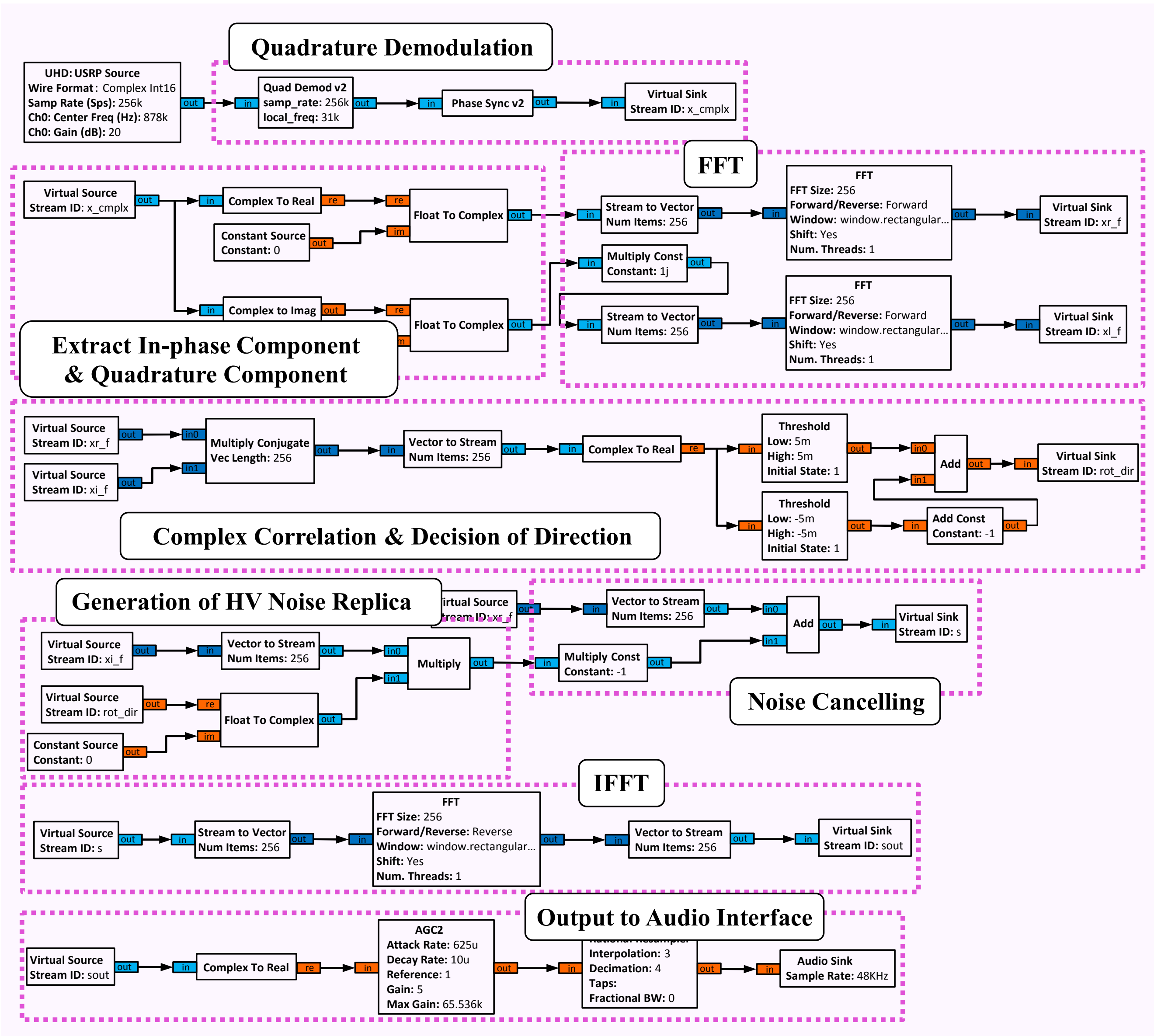


Fig. 9 Signal flow-graph of noise canceling system.

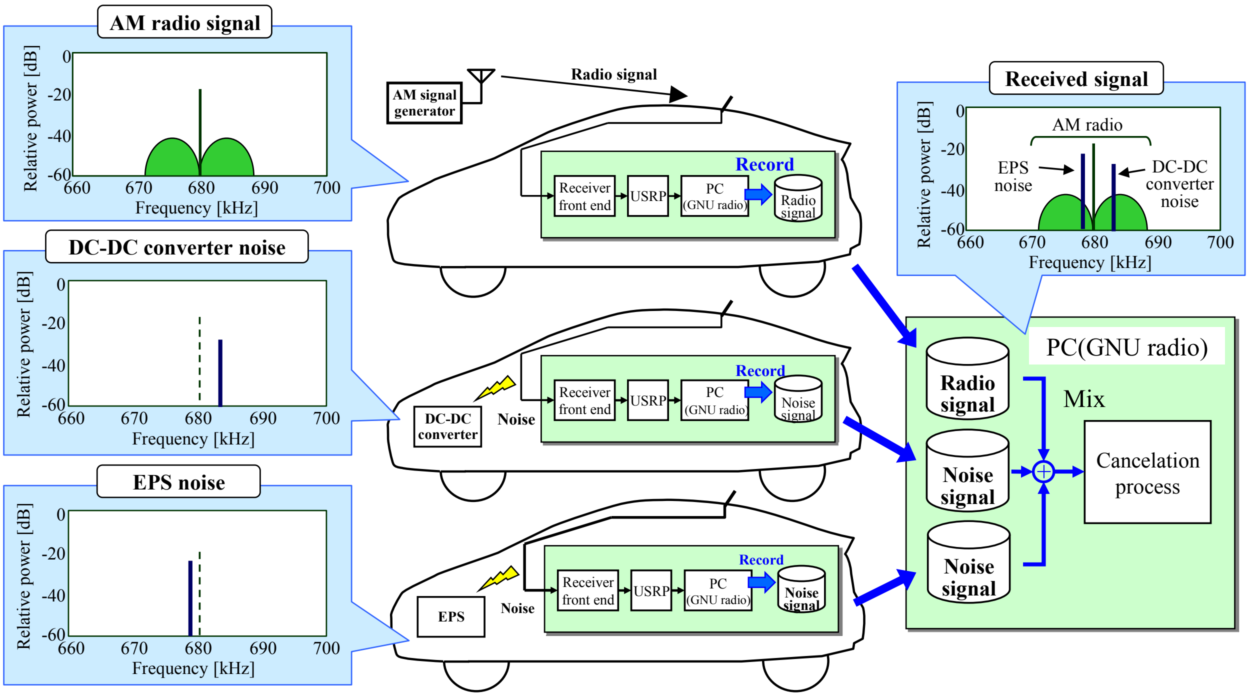
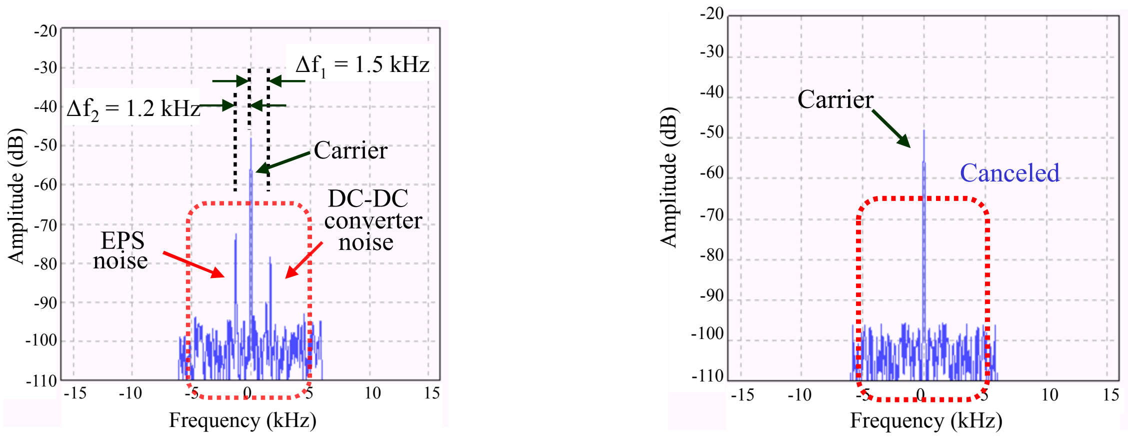


Fig. 10 Experimental method.



(a) Received signal (b) Canceling output

Fig. 11 Canceling effect on DC-DC converter noise and EPS noise.

eliminated almost entirely using the proposed method. A noise suppression effect of more than 15 dB is achieved at this moment. At the same time, it is confirmed that the audible tone peculiar to the harmonic noise is eliminated by the proposed method.

6. Conclusions

The electromagnetic noise (HV noise) generated by a power control unit (DC-DC converters, inverters), electric power steering (EPS) control modules, and other power electronics devices in an HV, give rise to serious AM radio receiver interference. In this paper, we have presented a new electromagnetic noise suppression system for an AM radio, using the quadrature component of the received signal.

In this method, the AM radio signal being interfered with by the electromagnetic noise is quadrature demodulated. A replica of the noise is then generated using the noise signal included in the quadrature component. Finally, the replica noise is subtracted from the in-phase component that includes the AM radio signal and the electromagnetic noise.

Compared to conventional methods, this method has the following advantages:

- This method does not need a noise sensor.
- The noise suppression effect of this method is superior to that for the noise sensing method, because a replica of the noise is generated by using the noise signal itself, which is then superimposed on the received signal.
- This method can be applied to noise that is or is not periodic.

Finally, we built a prototype of the radio receiver system and demonstrated that the system could reduce the DC-DC converter and EPS noise superimposed on the AM radio signal by more than 15 dB. As an added benefit, conventional noise suppression methods, such as noise filters and shielding wires, can be significantly simplified by applying this system to a radio receiver.

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Tomohisa Harada
Research Field:
- Digital Control System for Power Converter

Yoshiyuki Hattori
Research Fields:
- Electronic Devices for Automotive Application
- Electromagnetic Compatibility for Hybrid Vehicle

Academic Degree: Dr.Eng.
Academic Societies:
- The Institute of Electronics, Information and Communication Engineers
- The Institute of Electrical Engineers of Japan
- Society of Automotive Engineers of Japan

Shinya Ito*
Research Field:
- Noise Cancelling Technologies

Academic Societies:
- IEEE
- The Institute of Electronics, Information and Communication Engineers

Mitoshi Fujimoto*
Research Fields:
- Adaptive Arrays, Interference Cancellation
- DOA Estimation,
- MIMO Technology

Academic Degree: Dr.Eng.
Academic Societies:
- IEEE
- The Institute of Electronics, Information and Communication Engineers
- The Institute of Image Information and Television Engineers

Awards:
- Distinguished Service Award from the IEICE Communications Society, 2005
- Best Tutorial Paper Award from the IEICE Communications Society, 2013

Toshikazu Hori*
Research Fields:
- Antennas
- Propagation
- Printed Antennas
- Metamaterial
- Metasurface

Academic Degree: Dr.Eng.
Academic Societies:
- IEEE
- Union Radio-Scientifique Internationale
- The Institute of Electronics, Information and Communication Engineers
- The Institute of Image Information and Television Engineers

* University of Fukui