9.6 A 3.9kHz-Frame-Rate Capacitive Touch System with Pressure/Tilt Angle Expressions of Active Stylus Using Multiple-Frequency Driving Method for 65" 104×64 Touch Screen Panel

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As the demand for interactive displays continues to increase, capacitive touch systems (CTSs) with stylus-based drawing have become indispensable [1-4]. Passive styli are widely used because of their low-cost implementation, but have low SNR and limited drawing expressions [1]. Active styli have gained interest to solve these problems [4]. The pressure of an active stylus can be expressed using a pressure-to-capacitance transducer [3,4], but the tilt angle has not been reported yet. In addition, analog front-end (AFE) ICs with high frame rates are in demand in response to the fast movements of finger and active styli. Conventional AFE ICs adopt a parallel driving method (PDM) to achieve high SNR, but suffer from low frame rates because the number of rows and columns of the driving matrix increases with the number of TX electrodes [3]. In this paper, an AFE IC with high frame rate using a multiple-frequency driving method (MFDM) is proposed for response to fast movements of fingers and active styli, while expressing both the pressure and tilt angle of the active stylus.

Figures 9.6.1 and 9.6.2 show the block diagram of the CTS and the operational principle of the MFDM, respectively. To avoid the influence of external noise sources such as hum, display, and switched-mode power supply noises [2], the AFE IC employs an FFT processor to directly acquire a spectrum of external noises without providing excitation signals ($V_{EXT1-64}$) and a stylus signal (V_{STY}) to the TSP from the excitation circuit and active stylus, respectively. Then, the MCU observes the external noise spectrum and locates the frequencies of excitation signals (f_1-f_{64}) and stylus signals (f_{S1}-f_{S3}) in the low-noise region, as shown in Fig. 9.6.2. To increase the frame rate, the AFE IC using the MFDM simultaneously sends $V_{EXT1-64}$ to all TX electrodes and controls the phase and amplitude of $V_{EXT1-64}$ to protect the readout circuits from the incoming signal overflow. When the active stylus touches the TSP, it sends V_{STY} to the TSP. When the active stylus is touched with pressure and tilt, it changes f_{S2} and f_{S3} to $f_{S2}+\Delta f_{S2}$ and $f_{S3}+\Delta f_{S3}$, respectively. The touched coordinates of the finger and active stylus are extracted in two phases when the presence of f_{S1}-f_{S3} in the frequency spectrum is detected. In the first phase when SEL_RT is high, the AFE IC acquires a spectrum of a charge signal (Q_S) induced by V_{EXT} and V_{STY} to extract the coordinate of the finger and the x-coordinate of the active stylus. In the second phase when SEL_RT is low, the AFE IC acquires a spectrum of Q_S induced by only V_{STY} to extract the y-coordinate of the active stylus without sending V_{EXT}. When the active stylus is not touched on the TSP, the AFE IC only operates in the first phase and skips the second phase. The MCU extracts the coordinates of the finger and active stylus according to the amplitudes of f_1-f_{64} and the presence of f_{S1}, respectively, and the pressure and tilt angle of the active stylus are extracted using Δf_{S2} and Δf_{S3}, respectively. Since the frame rate of the CTS is independent of the number of TX electrodes, it can be increased by increasing the minimum frequencies of V_{EXT} and V_{STY}. The wireless communication between the MCU and active stylus is carried out by transferring only the frequency information of f_{S1}-f_{S3} to the active stylus without the timing synchronization. Moreover, additional active stylus can be utilized using different f_{S1}-f_{S3}.

Figure 9.6.3 shows the block diagram of the AFE IC with the frequency response of the current conveyor II (CCII) [6]. In the excitation circuit, the direct digital synthesizer (DDS) generates the sinusoidal wave and the 1st-order low-pass filter (LPF) attenuates harmonics in the output signal of the DDS. The gain-controllable buffer (GCB) controls the amplitude of V_{EXT} and sends it to the TX electrode. The readout circuit consists of 104 input channels with CCIIs, followed by 13 channels with 16:2 MUXs and SAR-ADCs. The conventional charge amplifiers [2-5] occupy a large area due to capacitors, whereas the CCII, which converts Q_S to a voltage signal, occupies a small area by adjusting its gain according to the ratio of the input and output resistors (R_{IN} and R_{OUT}). Since a combination of the CCII and TSP operates as a band-pass filter like the charge amplifier, the external noise is reduced. Moreover, since the MCU observes the external noises and locates the excitation signals, complex circuits such as active filter and demodulator, which require large area and high power consumption, are not necessary to implement the AFE IC. Each SAR-ADC connected to 8 CCIIs through a 16:2 MUX operates at a frequency of 16MHz. The FFT processor converts 512 time-divided digital data of the 12b SAR-ADC to FFT data. Thus, a frame rate of 3906Hz is achieved using the AFE IC, which simultaneously sends $V_{EXT1-64}$ to 64 channel TX electrodes.

Figure 9.6.4 (top) shows the block diagram of the active stylus. The force gauge and gyro sensor detect the pressure and tilt angle, and drive the signal controller to adjust Δf_{S2} and Δf_{S3}, respectively. Three excitation circuits, which operate on the same principle of the excitation circuit in the AFE IC, generate three sinusoidal waves whose frequencies are f_{S1}-f_{S3}. The mixer combines the generated waves and transfers them to the TSP via the buffer. To reduce power consumption, the active stylus generates V_{STY} only when it touches the TSP and its touch state is detected by the pressure sensor. A coordinate-extraction method of the self-capacitance sensing is used to extract the coordinate of the active stylus as shown in Fig. 9.6.4 (bottom).

The CTS is implemented with a 65" 104×64 TSP using a mesh structure, of which both the TX and RX electrodes have a 10.0μm thickness Ag with a sheet resistance of less than 5.0Ω/square. Thus, the total resistances of the TX and RX electrodes are less than 7kΩ and 4kΩ, respectively. The TSP is covered with a 4.0mm thickness glass and mounted on the full-/ultra-HD LCD with a 3.0mm air gap.

The measured frequency spectra of the CTS are shown in Fig. 9.6.5 (left); Fig. 9.6.5 (left-top) when the external noise (fluorescent lamp) is directly induced into the TSP, Fig. 9.6.5 (left-middle) when the finger is untouched or touched, and Fig. 9.6.5 (left-bottom) when the active stylus is touched with different pressure strength and tilt angle. As shown in Fig. 9.6.5 (left-middle), the FFT data increases with the excitation frequency because the amount of Q_S induced into the readout circuit proportionally increases with the excitation frequency. As shown in Fig. 9.6.5 (left-bottom), f_{S2} varies from 906.3 to 1061.5kHz according to the pressure strength of the active stylus. In addition, f_{S3} varies from 1076.1 to 1178.7kHz with the change of the tilt angle from 0 to 45°. Since the frequency resolution of the FFT is designed to be 2.9kHz, the active stylus can express the pressure and tilt angle with 6b resolution. Figure 9.6.5 (right) shows the raw FFT data of the 5-finger and active stylus, and the demonstration of the proposed CTS with a 65" 104×64 TSP. Figure 9.6.6 shows the performance summary of the CTS in comparison with previous works. The proposed CTS was measured with an LCD turned on.

Figure 9.6.7 shows the die micrograph of the AFE IC, which has a die size of 42.25mm^2 and uses a 256-pin Low-Profile Quad Flat Package (LQFP).

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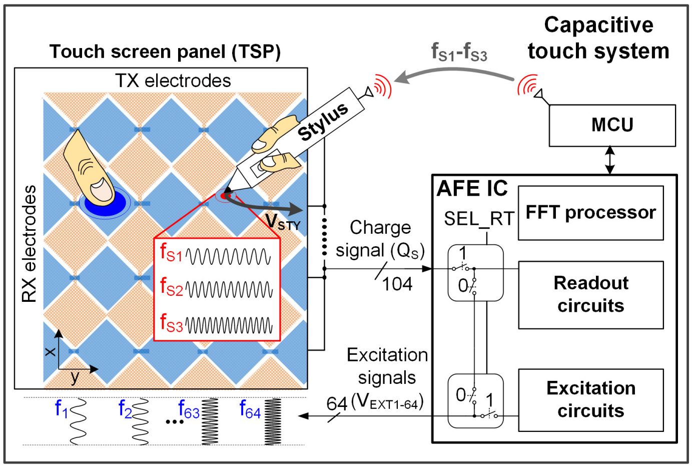

Figure 9.6.1: Block diagram of the capacitive touch system (CTS).

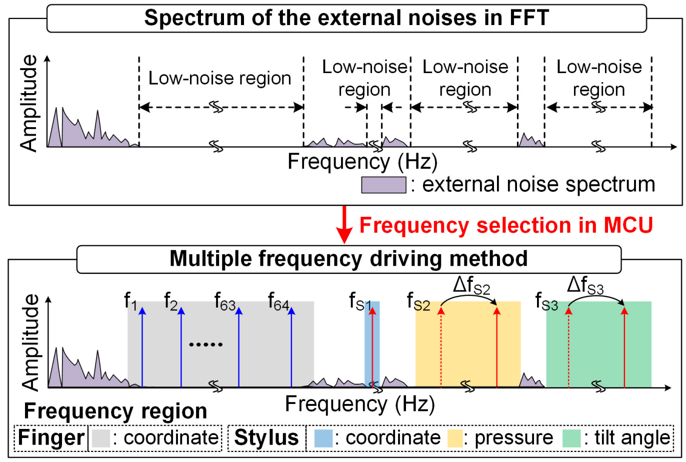

Figure 9.6.2: Operational principle of the multiple-frequency driving method (MFDM).

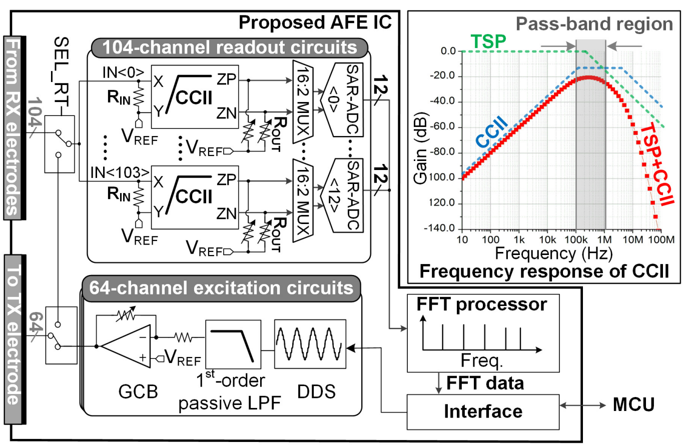

Figure 9.6.3: Block diagram of the AFE IC with the frequency response of the current conveyor II (CCII).

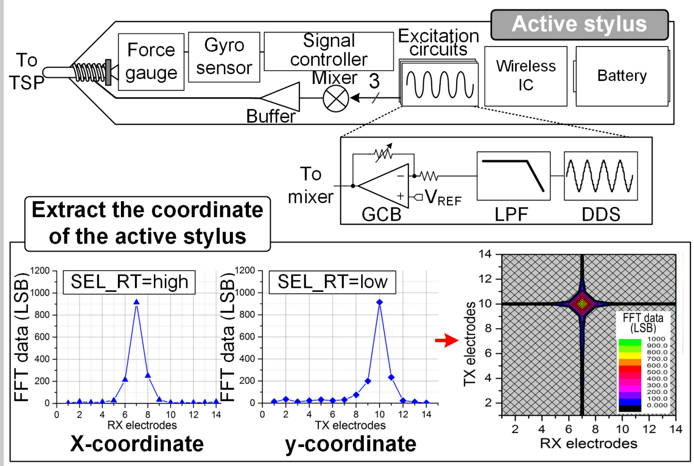

Figure 9.6.4: Block diagram of the active stylus (top) and extracted coordinate of the active stylus (bottom).

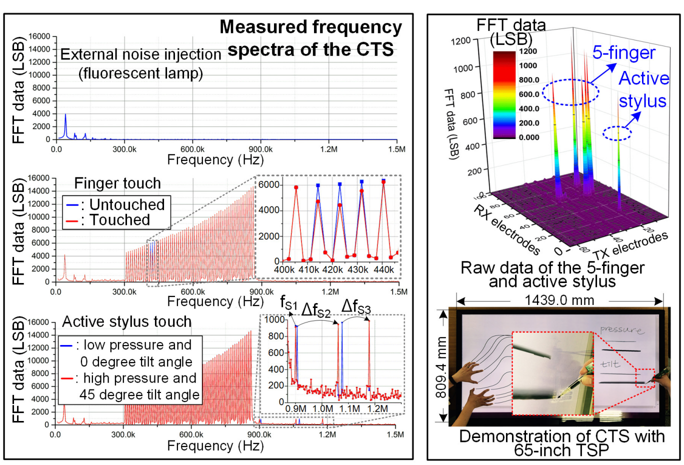

Figure 9.6.5: Measured frequency spectra of the CTS (left) and the raw touch data and the demonstration of the CTS with a 65-inch 104×64 TSP (right).

		This work	ISSCC' 13 [2]	ISSCC' 15 [3]	ISSCC' 15 [4]	ISSCC' 16 [5]
Process		0.13-μm CMOS	0.18-μm CMOS	0.18-μm BCD	85-nm CMOS	0.18-μm CMOS
TSP size		65-inch	5-inch	10.1-inch	13-inch	12.2-inch
# of electrodes		TX: 64 RX: 104	TX: 30 RX: 24	TX: 48 RX: 32	TX: 35 RX: 57	TX: 36 RX: 64
Frame rate		3906 Hz	240 Hz	240 Hz	240 Hz	85~385 Hz
SNR	Stylus (1mm)	Active: 50.1 dB Passive: 41.0 dB	Active: N/A Passive: 35.0 dB	Active: N/A Passive: 49.0 dB	Active: 41.0 dB Passive: 38.0 dB	Active: N/A Passive: 49.0 dB
	Finger	61.0 dB	55.0 dB	62.0 dB	N/A	49.0 dB
Stylus pen	Pressure	Yes (6-bit)	No	Yes (6-bit)	No	No
	Tilt	Yes (6-bit)	No	No	No	No
Supply		1.5/3.3 V	2.5~3.3 V	N/A	1.2/3.3 V	2.7~3.3 V
Power		96.3 mW (Analog+digital)	52.8 mW	30 mW	N/A	94.5 mW
Chip area		42.25 mm² (Analog+digital)	14.9 mm²	14.7 mm²	12.5 mm²	36.0 mm²
Chip area / electrode		6347.7 μm²	20694.4 μm²	9570.3 μm²	6265.7 μm²	15625.0 μm²

Figure 9.6.6: Performance summary for the AFE IC in comparison with previous works.

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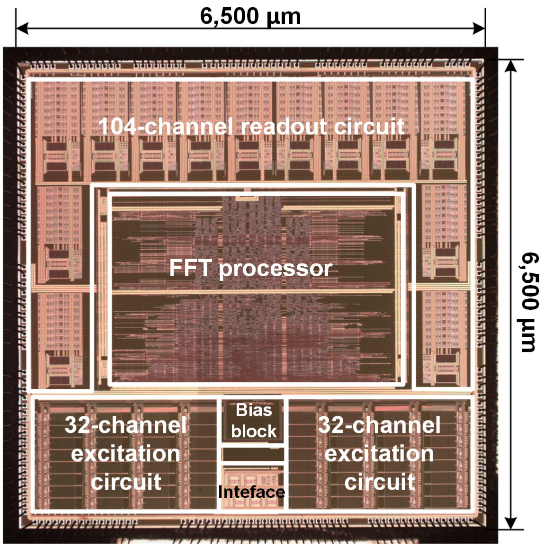

Figure 9.6.7: Die micrograph of the AFE IC.