Magnetization profile modulation in small-flip-angle balanced SSFP

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Introduction

In the balanced Steady State Free Precession (balanced SSFP) technique, the magnetization profile changes with off-resonance frequency. This profile has been used in water/fat separation [1]. Recently, Miller, et al. [2] proposed a new fMRI technique based on small-flip-angle balanced SSFP. This method, Blood Oxygenation Sensitive Steady State (BOSS), utilizes a sharp phase transition in the on-resonance band. Here, we present a method to modulate the magnetization profile in small-flip-angle balanced SSFP by changing the flip angle or RF phase. We also present a simple formula for this technique and show a discrete Fourier transform relationship between the magnetization profile and off-resonance frequency in small-flip-angle balanced SSFP.

Theory

The magnetization profile of balanced SSFP at a small RF flip angle is shown in Fig. 1. When the flip angle is small (2° at TR = 10ms here), the profile has a peak transverse magnetization at the zero frequency and also at n/TR frequencies. If the RF flip angle is very small ($\cos\alpha \cdot e^{-\tau/T_1} \approx 1$, τ *is the starting time of the readout*), we can neglect both T_1 relaxation and the effect of the flip on transverse magnetization, so the resulting magnetization can be considered as a sum of previous magnetizations with T_2 decay and off-resonance rotation ($\phi_{off} = \omega_{off} \cdot t$). This can be formulated as follows,

$$Mxy = \sum_{k=0}^{n} \sin\alpha \cdot e^{-(kTR+TE)/T_2 - j\omega_{off}(kTR+TE)} = \sin\alpha \cdot e^{-TE/T_2 - j\omega_{off}TE} \cdot \sum_{k=0}^{n} e^{-kTR/T_2} e^{-jk\omega_{off}TR} \qquad \text{[Eq.1]}$$

where n is large enough to make $e^{-nTR/T_2} \approx 0$. This result shows that a magnetization profile is a discrete Fourier transform of an exponential decaying function based on off-resonance frequency. Neglecting common terms in front of the summation, this becomes $Mxy \propto \boldsymbol{DFT}(e^{-kTR/T_2})$, where $\boldsymbol{DFT}$ represents the discrete Fourier transform. Since the given function is an exponential decay with zeros when time is negative, the Fourier transform pair is Lorentzian as shown in Fig.2b. It has strong similarity to the previously simulated small flip angle profile shown in Fig. 1. When we include an RF flip angle modulation ($\alpha_1, \alpha_2, \cdots, \alpha_n$) and an RF phase modulation ($\phi_1, \phi_2, \cdots, \phi_n$) the previous formula alters to

$$Mxy = e^{-TE/T_2 - j\omega_{off}TE} \cdot \sum_{k=0}^{n} F(k) \cdot e^{-kTR/T_2} \cdot e^{-jk\omega_{off}TR}, \qquad \text{[Eq.2]}$$

$$\text{where } F(k) = \sin\alpha_k \cdot \exp\left(-j\sum_{m=0}^{k}\phi_m\right)$$

This equation can be considered as a convolution of $\boldsymbol{DFT}(F(k))$ and $\boldsymbol{DFT}(e^{-kTR/T_2})$. As a result, by utilizing RF flip angle and phase, the magnetization profile can be changed. Moreover, we can predict the magnetization profile from this formula.

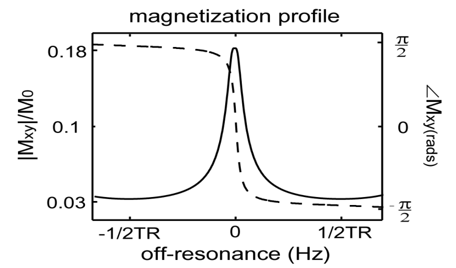
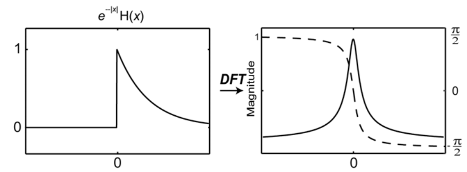


Figure 1. Small flip angle (2°) balanced SSFP profile



(a) (b)

Figure 2. (a) Exponential decaying function and (b) its Fourier transform pair

Simulation and Experiment

Simulations were performed by solving the Bloch equation for the steady state. Simulation parameters were TR = 10ms(EX.1) / 20ms(EX.2), TE = TR/2, T1 = 780ms and T2 = 100ms.

Example 1. RF phase cycling modulation with phase cycle of π. The simulated magnetization profile is shown in Fig. 3. From Eq. 2, π phase cycle becomes $\boldsymbol{DFT}(\sin\alpha_k \cdot \exp(-jk\pi)) = \sin\alpha \cdot \boldsymbol{DFT}(\cos k\pi)$. The $\boldsymbol{DFT}$ of $\cos n\pi$ has one impulse at the positive half of the sampling frequency and another at the negative half. The resulting profile is a convolution of these impulses with Fig. 2. This explanation shows a good agreement with the simulation.

Example 2. RF flip angle modulation with $\alpha_k = 2 + 4\cos(2\pi k/4)$**.** The Fourier transform of this will give one impulse at on-resonance frequency, at –1/(4T), and at 1/(4T). However, since the flip angle cycles as $\boldsymbol{DFT}$ range (k = 0 to n) changes over time the profile also changes. As a result, we will have four different profiles in the steady state. The simulation result from the Bloch equation is shown in Fig. 4 and an experiment (a ball-shape phantom, 50Hz off resonance across x axis) result is shown in Fig. 5. The experimental and simulated results agree very well with the prediction of our convolution model.

Discussion and Conclusion

Here, we showed a simple discrete Fourier transform relationship in small-flip-angle balanced SSFP magnetization profile. We also explained how the profile is modulated by flip angle or phase change and showed a simple equation to predict to the profile modulation. Two examples of flip angle modulation and RF phase modulation were simulated and showed an excellent intuitive match with Eq. 2. The phantom scan result further illustrates the usefulness of this technique. This technique can be applied to BOSS fMRI to widen the transition band or to make multiple transition bands over 1/TR frequency range. Additionaly considerations will be increased imaging time by unused readout echoes or ghosting due to the profile change at the different TRs.

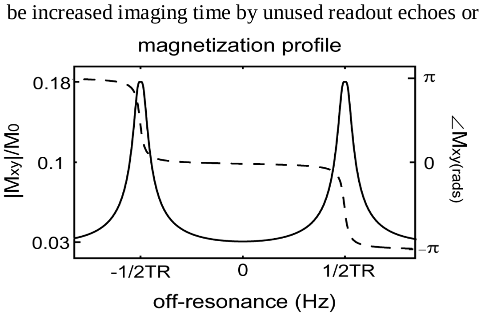


Figure 3. The simulation result of RF phase modulated SSFP profile: $\phi_k = \pi$

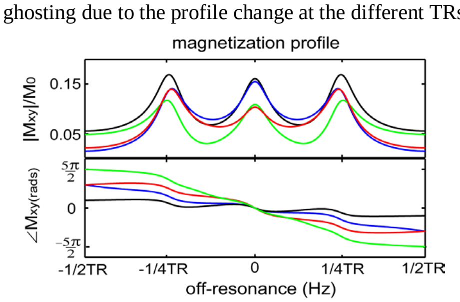
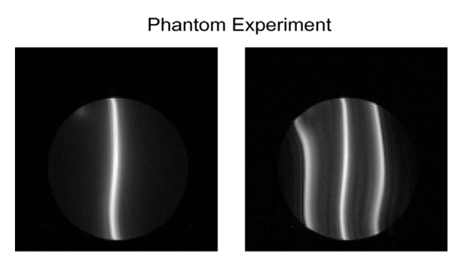


Figure 4. The simulation result of RF flip angle modulated SSFP profile: $\alpha_k = 2 + 4\cos(2\pi k/4)$



(a) (b)

Figure 5. The phantom experiment result of RF flip angle modulated SSFP profile (a) $\alpha = 4°$ and (b) $\alpha_k = 2 + 4\cos(2\pi k/4)$:The image is from one profile

References

[1] Vasanawala, et al. MRM 42:876(1999)

[2] Miller, et al. MRM. 50:675 (2003)