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An analysis of phase-modulated heteronuclear dipolar decoupling sequences in solid-state nuclear magnetic resonance

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ABSTRACT

The design of variants of the swept-frequency two-pulse phase modulation sequence for heteronuclear dipolar decoupling in solid-state NMR is reported, their performance evaluated, and compared with other established sequences like TPPM and SPINAL. Simulations performed to probe the role of the homonuclear ^{1}H–^{1}H bath show that the robustness of the decoupling schemes improves with the size of the bath. In addition, these simulations reveal that the homonuclear ^{1}H–^{1}H bath also leads to broad baselines at high MAS rates. Results from a study of the SPINAL decoupling scheme indicate that optimisation of the starting phase and phase increment improves its performance and efficiency at high MAS rates. Additionally, experiments performed on a liquid crystal display the role of the initial phase in SPINAL-64 and sequences in the SW$_f$-TPPM family.

1. Introduction

Heteronuclear dipolar decoupling combined with magic-angle spinning (MAS) is necessary to obtain narrow lines in solid-state NMR spectra of rare spins when they are coupled to abundant spins [1–3]. This is the case whilst recording ^{13}C spectra of organic compounds, amino acids, proteins, and drugs as ^{13}C is a rare spin and is dipolar coupled to the abundant ^{1}H spins. Decoupling improves resolution and is also naturally accompanied by an increase in sensitivity.

A continuous burst of radio-frequency (RF) irradiation on the ^{1}H spins, like in solution-state NMR for heteronuclear *J* decoupling, was observed to effect a certain degree of heteronuclear dipolar decoupling in solid-state NMR. This scheme, called CW decoupling [4], was used routinely till the mid 1990s when a paradigm shift occurred with the introduction of two-pulse phase modulation (TPPM) [5] after which many decoupling sequences were introduced [6–9]. A rigorous understanding of the spin interactions, higher-order terms, and cross terms with and among the various spin interactions has proved to be useful in formulating better decoupling sequences [10]. Several drawbacks of the CW scheme were also noticed with the advent of more sophisticated experimental approaches, for instance, high-speed MAS probes. It was, for example, observed that the spectral lines actually broaden out with increasing MAS frequencies contrary to expectation [10]. This is now attributed to the reduction of the homonuclear ^{1}H–^{1}H dipolar couplings with increasing MAS frequencies. Detailed description of the progress made in this problem can be found in the recent reviews [6,7].

As already mentioned TPPM [5] was the first sequence to offer considerable improvement over CW in decoupling. This scheme consists of two pulses of equal lengths (denoted by τ) which differ in phase (denoted by 2ϕ). Achieving optimum performance with TPPM involves optimisation of τ as well as ϕ. The mechanism of phase modulation in TPPM together with a criterion for efficient decoupling was worked out recently by Leskes et al. on the basis of bimodal Floquet theory [11]. It was shown that careful optimisation of τ and ϕ is needed to satisfy the decoupling conditions.

A few of the decoupling sequences introduced after TPPM that deserve merit are the following. An improvement of TPPM was introduced by Fung et al. which consists of TPPM blocks with discretely incremented phases and termed small phase incremental alteration (SPINAL) [12]. Although originally designed for static samples like liquid crystals SPINAL performs admirably for spinning samples. Based on the arguments of Leskes et al., the efficiency of this sequence can be understood in terms of its ability to satisfy decoupling conditions owing to alteration of the phases. Another modification of TPPM with continuous phase variation was proposed by Paëpe et al. named cosine modulation (CM) [13,14]. Unlike TPPM, where the phase is square-wave modulated, CM involves generating a cosine profile with different initial values and time period for optimum performance by automated iteration.

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This study was fruitful in unraveling the mechanism of decoupling, but its experimental implementation is involved. Gerbaud et al. have convoluted a Gaussian with cosine modulation to effect heteronuclear dipolar decoupling and also addressed some issues related to the robustness of decoupling sequences [15]. Khitrin et al. have designed decoupling sequences by convoluting many cosine modulations that lead to certain degree of robust performance [16]. Their semi-quantitative arguments suggested the requirement of an additional modulation on TPPM for improved heteronuclear dipolar decoupling.

An altogether different strategy for designing heteronuclear dipolar decoupling sequences was adopted by Levitt and coworkers who demonstrated a set of *C*-sequences for heteronuclear dipolar decoupling [17] based on the symmetry properties of tensorial interactions [18]. Riedel et al. have demonstrated improvement in *C*-sequences by using adiabatic pulses [8].

A conceptually distinct approach, called XiX, was adopted by Meier and coworkers [19]. Its origin could be traced to an earlier attempt by Tekely [20]. Unlike the phase-modulated sequences, the decoupling efficiency of XiX improves as the MAS frequency increases.

Recently, we have designed robust decoupling sequences for both MAS experiments [9] and static cases [21]. Our approach consisted of modulating TPPM blocks by discretely changing the duration of each block in an adiabatic fashion. The resulting scheme, swept-frequency TPPM ($\mathrm{SW_f}$-TPPM), due to the adiabatic sweep was shown to generate robustness with respect to various experimental parameters. This was also exemplified in the theoretical approach based on bimodal Floquet treatment [11]. The $\mathrm{SW_f}$-TPPM sequence also offers significant intensity enhancement of MQMAS spectra of quadrupolar samples and is again insensitive to misset of various experimental parameters [22].

We here report on the experimental investigation of the performance of modulated TPPM sequences under MAS and especially the role played by the depth of the phase modulation ϕ for $\mathrm{SW_f}$-TPPM scheme. Simulations and experiments show that TPPM fails at high MAS rates a result which was already demonstrated for TPPM [19]. The same is true for $\mathrm{SW_f}$-TPPM scheme unless the cycle time is changed or additional modulations are imposed. Experimental corroboration of the earlier observations of the optimum initial value of $\phi = 15^\circ$ in the SPINAL scheme instead of the generally accepted $\phi = 10^\circ$ in the case of static liquid crystals will also be shown. The manuscript deals with: the design strategy of various decoupling schemes on the lines of $\mathrm{SW_f}$-TPPM, a revisit of the efficiency of the $\mathrm{SW_f}$-TPPM decoupling scheme, probing the role of the homonuclear $^1\mathrm{H}$–$^1\mathrm{H}$ coupling on heteronuclear dipolar decoupling via numerical simulations, a discussion on the study of various newly designed $\mathrm{SW_f}$-TPPM analogues and SPINAL, and a study of decoupling in a liquid-crystal to discern the effect of the starting phase of the sequence on the decoupling efficiency.

2. Design of the pulse sequences

A detailed study of heteronuclear dipolar decoupling was recently done by Leskes et al. laying down conditions for decoupling and looking into resonance conditions for decoupling with respect to various experimental parameters [11]. $\mathrm{SW_f}$-TPPM was designed by modulating the pulse length in TPPM with tangential profile. The tangential profile ensures that the resonance conditions for decoupling are met for a range of values of the pulse duration. Other variants reported here are designed by modulating the pulse length albeit the profiles are different. These sequences are designed as variants of $\mathrm{SW_f}$-TPPM by sweeping across the aforementioned resonance condition in many possible ways. Thus, we have a diversity of distribution of frequency components in these sequences which appear in the respective power spectra.

To frame the discussion in the later sections, we outline the design strategy of the various decoupling sequences. The new RF modulated decoupling schemes are built with TPPM as the building block. TPPM consists of two pulses of length τ with phases ϕ and $-\phi$. It is notated as $[\tau_\phi \tau_{-\phi}]$. Both τ and ϕ need to be experimentally optimised for maximum decoupling efficiency.

Taking $[\tau_\phi \tau_{-\phi}]$ as the building block, Fung and coworkers formulated a recipe which combines phase variations of the TPPM blocks and supercycling to obtain sequences of the SPINAL family [12]. The basic SPINAL scheme (SPINAL-8) has the form $[\tau_\phi \tau_{-\phi}]$ $[\tau_{\phi+\delta} \tau_{-(\phi+\delta)}][\tau_{\phi+2\delta} \tau_{-(\phi+2\delta)}][\tau_{\phi+\delta} \tau_{-(\phi+\delta)}]$, where ϕ and δ are respectively the starting value and the increment of the phase. Generally ϕ and δ are taken to be 10° and 5°, respectively, in which case SPINAL-8 reads as $[\tau_{10} \tau_{-10}][\tau_{15} \tau_{-15}][\tau_{20} \tau_{-20}][\tau_{15} \tau_{-15}]$. Notating the SPINAL-8 block as Q and defining $\overline{Q}$ as $[\tau_{-10} \tau_{10}][\tau_{-15} \tau_{15}]$ $[\tau_{-20} \tau_{20}][\tau_{-15} \tau_{15}]$, SPINAL-16, SPINAL-32, and SPINAL-64 are obtained as $Q\overline{Q}$, $Q\overline{QQ}Q$, and $Q\overline{QQ}Q\overline{Q}QQ\overline{Q}$, respectively and which was called supercycling in the original report [12]. A reported advantage of SPINAL over TPPM is the need to experimentally optimise only the pulse length and not the phase. Here, with a goal to enhance the performance of SPINAL, we have relaxed this requirement and attempted to find the optimum value of both the initial phase (ϕ) and increment (δ) at various MAS rates. Earlier we had investigated the effect of the initial phase keeping the increment steps fixed at $\delta = 5^\circ$ and notated such sequences as SPINAL-64_x where x was the initial phase [21].

$\mathrm{SW_f}$-TPPM is obtained by modulating the pulse length of TPPM blocks, i.e. by varying the values of τ. It can be represented by specifying the pulse width (τ) of each TPPM pair with the phase ϕ a constant and may be notated as $\{[0.78\tau_\phi 0.78\tau_{-\phi}][0.86\tau_\phi 0.86\tau_{-\phi}]$ $[0.94\tau_\phi 0.94\tau_{-\phi}][0.96\tau_\phi 0.96\tau_{-\phi}][0.98\tau_\phi 0.98\tau_{-\phi}][\tau_\phi \tau_{-\phi}][1.02\tau_\phi 1.02\tau_{-\phi}]$ $[1.04\tau_\phi 1.04\tau_{-\phi}]$ $[1.06\tau_\phi 1.06\tau_{-\phi}][1.14\tau_\phi 1.14\tau_{-\phi}][1.22\tau_\phi 1.22\tau_{-\phi}]\}$. In other words, 11 TPPM blocks make up this sequence with the pulse lengths varying from 0.78τ to 1.22τ in the manner given above. Although the central pulse pair duration τ may have to be optimised for an enhanced performance, a value corresponding to flip angle of 180° suffices in most cases of practical interest. The numbers multiplying τ provide control over the profile of the sweep and a recipe to generate new sequences. In this fashion many profiles were designed by us, called $\mathrm{SW_f}$-TPPM sequences in general, with qualitative differences in their power spectra.

The profiles of the new $\mathrm{SW_f}$-TPPM analogues and their power spectra are given in Fig. 1 in the left and right columns, respectively. The numbers plotted on the ordinate in the left column of Fig. 1 are the multiplicative factors (denoted by f_i) that determine the profile. The numerical values are given in Table 1. We now summarise how the f_i's of the $\mathrm{SW_f}$-TPPM family were obtained. All of them are composed of TPPM-like blocks with the central pulse pair having a pulse length close to that corresponding to a flip angle of 180°. The duration of the pulses in this block is denoted as 1.

- In $\mathrm{SW_f}(\tau)$-TPPM the pulse widths were swept linearly from 0.75 to 1.25 times τ with an increment of 0.05. In equation form the f_i are given by $f_i = 0.75 + 0.05 \times (i - 1)$ where i is the number of the TPPM block.
- The numerical factors of $\mathrm{SW_f^{inv}}$-TPPM are given as $f_i = 1/x_i$ where x_i is given by $1.5 - 0.1 \times (i - 1)$ and i in turn is the number of the TPPM block. In other words, x_i decreases linearly from 1.5 to 0.5.
- The two sequences $\mathrm{SW_f^{tan_1}}$-TPPM and $\mathrm{SW_f^{tan_2}}$-TPPM were generated by evaluating the function $1 + \tan\theta$ at 15 equidistant points as θ varied between $\approx -20^\circ$ and $\approx 20^\circ$ in the case of the former and between $\approx -14^\circ$ and $\approx 14^\circ$ in the latter. The case of