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Construction and Parameterization of a Polynomial Seventh-Order Two-Parameter Interpolation Kernel

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Abstract: *Convolutional interpolation is widely used in digital signal processing because of its computational efficiency and suitability for real-time applications. The interpolation accuracy strongly depends on the characteristics of the applied interpolation kernel. This paper presents the construction and parameterization of a polynomial seventh-order two-parameter (2P) interpolation kernel, which, to the best of the authors' knowledge, has not been previously described in the scientific literature. The kernel is formulated as a set of piecewise seventh-order polynomials subject to the required constraints at the interpolation nodes. Two independent coefficients are introduced as the kernel parameters α and β, while the remaining polynomial coefficients are expressed as functions of these parameters. The influence of α and β on the time-domain and amplitude characteristics of the proposed kernel is analyzed and compared with the windowed sinc kernel. The results demonstrate that variations in the kernel parameters modify both characteristics, while the second parameter β provides an additional degree of freedom for finer adjustment of the kernel characteristics. The proposed parameterization provides a basis for further optimization of the seventh-order 2P interpolation kernel for specific digital signal and image processing applications.*

Keywords: *Convolution; interpolation; polynomial kernel; Amplitude characteristics*

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I. INTRODUCTION

In digital signal processing (DSP), interpolation is widely used to estimate signal values at positions between two neighboring discrete samples [1], [2]. It is applied in various fields, including image, audio, and speech processing. In image processing, interpolation is commonly required for spatial and geometric transformations, image rotation, and related operations [3], [4]. In speech processing, interpolation is also employed in applications such as fundamental frequency estimation for the analysis of the emotional and health status of a speaker, as well as for semantic and syntactic speech analysis and speech synthesis [5]. Interpolation algorithms used in DSP, particularly in real-time applications, are required to provide both high accuracy and high computational efficiency. Convolution-based interpolation meets these requirements and is therefore widely used in DSP applications [6]. This approach is based on an interpolation kernel, r, through which the interpolation is performed by convolving a discrete signal, such as an image, speech, or audio signal, with the corresponding kernel [7]. The accuracy of the resulting interpolation is directly influenced by the properties of the applied interpolation kernel.

The ideal interpolation kernel is defined by the sinc function, $\mathrm{sinc}(x) = \sin(x)/x$, and is commonly referred to as the sinc kernel in the scientific literature. In the time domain, this kernel extends over the entire interval $(-\infty, +\infty)$. Its spectral characteristic corresponds to an ideal rectangular frequency response, with a perfectly flat passband and stopband and an infinitely large slope in the transition band. Such ideal characteristics cannot be practically realized, and therefore various finite-support approximations of the sinc kernel have been developed [8].

Through windowization, the infinite length of the sinc kernel can be reduced by applying a window function, resulting in a finite-length sincw kernel suitable for convolutional interpolation. However, the spectral characteristic of the sincw kernel exhibits significant ripples in both the passband and stopband, as well as a finite slope in the transition band. Consequently, the interpolation accuracy is unsatisfactory. Therefore, an important problem in DSP is the construction of a finite-length interpolation kernel of length L and an appropriate shape that provides a satisfactory approximation to the sinc kernel in both the time and spectral domains.

Polynomial functions of low order, $n \leq 7$, have been widely used to approximate the sinc kernel. The simplest polynomial interpolation kernel is the zeroth-order kernel, in which the interpolated value is determined by selecting the nearest-neighbor sample. Although this approach enables very fast convolutional interpolation, it results in a relatively large interpolation error. To improve interpolation accuracy, linear (first-order, $n = 1$), cubic (third-order, $n = 3$) [2], quintic (fifth-order, $n = 5$), and septic (seventh-order, $n = 7$) one-parameter (1P, α) interpolation kernels have been developed [9]. As the order n of the 1P kernels increases, their interpolation accuracy generally improves. In addition, the time and spectral domain characteristics of these kernels can be adjusted by varying the parameter α, enabling the optimization of the kernel for a specific interpolation requirement.

To achieve greater flexibility in adapting the interpolation kernel to the characteristics of a specific signal, two-parameter (2P, α, β) interpolation kernels have subsequently been developed. The third-order 2P kernel was first proposed in [10], followed by the development of a fifth-order 2P kernel [11]. However, to the best of our knowledge, the construction of a seventh-order polynomial two-parameter (2P, α, β) interpolation kernel has not yet been described in the scientific literature.

In this paper, the construction of a polynomial seventh-order two-parameter (2P, α, β) interpolation kernel is described. The kernel was constructed in accordance with the requirements that an interpolation kernel must satisfy, primarily concerning the similarity between the time-domain characteristics of the 2P kernel and the sinc kernel at all interpolation nodes [12], [13]. To satisfy these requirements, a system of 38 equations with 40 unknowns was first formulated. Two coefficients were then defined as the kernel parameters α and β, thereby parameterizing the kernel and providing an unambiguous solution to the system of equations. All parameterized coefficients of the polynomial seventh-order kernel are presented in a table. The effects of varying the parameters α and β on the kernel characteristics are presented graphically.

The paper is further organized as follows. Section 2 describes the construction and parameterization of the polynomial seventh-order 2P interpolation kernel. Section 3 analyzes the time-domain and amplitude characteristics of the 2P kernel and discusses the influence of its parameters. Finally, Section 4 is Conclusion.

II. CONSTRUCTION OF THE POLYNOMIAL SEVENTH-ORDER 2P KERNEL

The seventh-order two-parameter (2P) interpolation kernel was developed based on the seventh-order polynomial one-parameter (1P) kernel described in the literature [11]-[13]. The main objective of the proposed 2P kernel is to provide a more accurate approximation of the ideal sinc interpolation kernel over the interval (-5, 5). The kernel r is defined as:

$$r(s)=\begin{cases} a_{70}|s|^7+\ldots+a_{10}|s|+a_{00}, & |s|\leq 1 \\ a_{71}|s|^7+\ldots+a_{11}|s|+a_{01}, & 1<|s|\leq 2 \\ a_{72}|s|^7+\ldots+a_{12}|s|+a_{02}, & 2<|s|\leq 3 \\ a_{73}|s|^7+\ldots+a_{13}|s|+a_{03}, & 3<|s|\leq 4 \\ a_{74}|s|^7+\ldots+a_{14}|s|+a_{04}, & 4<|s|\leq 5 \\ 0, & \text{otherwise} \end{cases}, \tag{1}$$

The kernel consists of piecewise seventh-order polynomials defined over the subintervals (-5, -4), ..., (4, 5). These polynomials must satisfy the following constraints [12]: a) $r(0) = 1$, b) $r(s) = 0$ for $|s| = 1, \ldots, 5$ and c) $r^{(\ell)}(s)$ must be continuous at $|s| = 1, \ldots, 5$ where $\ell = 1, \ldots, 5$. Based on these constraints, the following system of equations is formulated:

$$r(0)=1 \Rightarrow a_{00}=1, \tag{2}$$

$$r(1)=0 \Rightarrow a_{70}+a_{60}+a_{50}+a_{40}+a_{30}+a_{20}+a_{10}+a_{00}=0, \tag{3}$$

$$r(2)=0 \Rightarrow 128a_{71}+64a_{61}+32a_{51}+16a_{41}+8a_{31}+4a_{21}+2a_{11}+a_{01}=0, \tag{4}$$

$$r(3)=0 \Rightarrow 2187a_{72}+729a_{62}+243a_{52}+81a_{42}+27a_{32}+9a_{22}+3a_{12}+a_{02}=0, \tag{5}$$

$$r(4)=0 \Rightarrow 16384a_{73}+4096d_{63}+1024d_{53}+256d_{43}+64d_{33}+16d_{23}+4d_{13}+d_{03}=0, \tag{6}$$

$$\lim_{s\to 1^-} r(s)=\lim_{s\to 1^+} r(s) \Rightarrow a_{70}+a_{60}+a_{50}+a_{40}+a_{30}+a_{20}+a_{10}+a_{00}=a_{71}+a_{61}+a_{51}+a_{41}+a_{31}+a_{21}+a_{11}+a_{01}, \tag{7}$$

$$\lim_{s\to 2^-} r(s)=\lim_{s\to 2^+} r(s)\Rightarrow 128a_{71}+64a_{61}+32a_{51}+16a_{41}+8a_{31}+4a_{21}+2a_{11}+a_{01} \\ =128a_{72}+64a_{62}+32a_{52}+16a_{42}+8a_{32}+4a_{22}+2a_{12}+a_{02}, \tag{8}$$

$$\lim_{s\to 3^-} r(s)=\lim_{s\to 3^+} r(s)\Rightarrow 2187a_{72}+729a_{62}+243a_{52}+81a_{42}+27a_{32}+9a_{22}+3a_{12}+a_{02} \\ =2187a_{73}+729a_{63}+243a_{53}+81a_{43}+27a_{33}+9a_{23}+3a_{13}+a_{03}, \tag{9}$$

$$\lim_{s\to 4^-} r(s)=\lim_{s\to 4^+} r(s)\Rightarrow 16384a_{73}+4096a_{63}+1024a_{53}+256a_{43}+64a_{33}+16a_{23}+4a_{13}+a_{03} \\ =16384a_{74}+4096a_{64}+1024a_{54}+256a_{44}+64a_{34}+16a_{24}+4a_{14}+a_{04}, \tag{10}$$

$$\lim_{s\to 5^-} r(s)=\lim_{s\to 5^+} r(s)\Rightarrow 78125a_{74}+15625a_{64}+3125a_{54}+625a_{44}+125a_{34}+25a_{24}+5a_{14}+a_{04}=0, \tag{11}$$

$$r^{(1)}(0)=0\Rightarrow \mathrm{a}_1\text{=}0, \tag{12}$$

$$\lim_{s\to 1^-} r^{(1)}(s)=\lim_{s\to 1^+} r^{(1)}(s)\Rightarrow 7a_{70}+6a_{60}+5a_{50}+4a_{40}+3a_{30}+2a_{20}+a_{10} \\ =7a_{71}+6b_{61}+5b_{51}+4b_{41}+3b_{31}+2b_{21}+b_{11}, \tag{13}$$

$$\lim_{s\to 2^-} r^{(1)}(s)=\lim_{s\to 2^+} r^{(1)}(s)\Rightarrow 448a_{71}+192a_{61}+80a_{51}+32a_{41}+12a_{31}+4a_{21}+a_{11} \\ =448a_{72}+192a_{62}+80a_{52}+32a_{42}+12a_{32}+4a_{22}+a_{12}, \tag{14}$$

$$\lim_{s\to 3^-} r^{(1)}(s)=\lim_{s\to 3^+} r^{(1)}(s)\Rightarrow 5103a_{72}+1458a_{62}+405a_{52}+108a_{42}+27a_{32}+6a_{22}+a_{12} \\ =5103a_{73}+1458a_{63}+405a_{53}+108a_{43}+27a_{33}+6a_{23}+a_{13}, \tag{15}$$

$$\lim_{s\to 4^-} r^{(1)}(s)=\lim_{s\to 4^+} r^{(1)}(s)\Rightarrow 28672a_{73}+6144a_{63}+1280a_{53}+256a_{43}+48a_{33}+8a_{23}+a_{13} \\ =28672a_{74}+6144a_{64}+1280a_{54}+256a_{44}+48a_{34}+8a_{24}+a_{14}, \tag{16}$$

$$\lim_{s\to 5^-} r^{(1)}(s)=\lim_{s\to 5^+} r^{(1)}(s)\Rightarrow 109375a_{74}+18750a_{64}+3125a_{54}+500a_{44}+75a_{34}+10a_{24}+a_{14}=0, \tag{17}$$

$$\lim_{s\to 1^-} r^{(2)}(s)=\lim_{s\to 1^+} r^{(2)}(s)\Rightarrow 42a_{70}+30a_{60}+20a_{50}+12a_{40}+6a_{30}+2a_{20} \\ =42a_{71}+30a_{61}+20a_{51}+12a_{41}+6a_{31}+2a_{21}, \tag{18}$$

$$\lim_{s\to 2^-} r^{(2)}(s)=\lim_{s\to 2^+} r^{(2)}(s)\Rightarrow 1344a_{71}+480a_{61}+160a_{51}+48a_{41}+12a_{31}+2a_{21} \\ =1344a_{72}+480a_{62}+160a_{52}+48a_{42}+12a_{32}+2a_{22}, \tag{19}$$

$$\lim_{s\to 3^-} r^{(2)}(s)=\lim_{s\to 3^+} r^{(2)}(s)\Rightarrow 10206a_{72}+2430a_{62}+540a_{52}+108a_{42}+18a_{32}+2a_{22} \\ =10206a_{73}+2430a_{63}+540a_{53}+108a_{43}+18a_{33}+2a_{23}, \tag{20}$$

$$\lim_{s\to 4^-} r^{(2)}(s)=\lim_{s\to 4^+} r^{(2)}(s)\Rightarrow 43008a_{73}+7680a_{63}+1280a_{53}+192a_{43}+24a_{33}+2a_{23} \\ =43008a_{74}+7680a_{64}+1280a_{54}+192a_{44}+24a_{34}+2a_{24}, \tag{21}$$

$$\lim_{s\to 5^-} r^{(2)}(s)=\lim_{s\to 5^+} r^{(2)}(s)\Rightarrow 131250a_{74}+18750a_{64}+2500a_{54}+300a_{44}+30a_{34}+2a_{24}=0, \tag{22}$$

$$r^{(3)}(0)=0\Rightarrow \mathrm{a}_{30}\text{=}0, \tag{23}$$

$$\lim_{s\to 1^-} r^{(3)}(s)=\lim_{s\to 1^+} r^{(3)}(s)\Rightarrow 210a_{70}+120a_{60}+60a_{50}+24a_{40}+6a_{30} \\ =210a_{71}+120a_{61}+60a_{51}+24a_{41}+6a_{31}, \tag{24}$$

$$\lim_{s\to 2^-} r^{(3)}(s)=\lim_{s\to 2^+} r^{(3)}(s)\Rightarrow 3360a_{71}+960a_{61}+240a_{51}+48a_{41}+6a_{31} \\ =3360a_{72}+960a_{62}+240a_{52}+48a_{42}+6a_{32}, \tag{25}$$

$$\lim_{s\to 3^-} r^{(3)}(s) = \lim_{s\to 3^+} r^{(3)}(s) \Rightarrow 17010a_{72} + 3240a_{62} + 540a_{52} + 72a_{42} + 6a_{32} = 17010a_{73} + 3240a_{63} + 540a_{53} + 72a_{43} + 6a_{33}, \tag{26}$$

$$\lim_{s\to 4^-} r^{(3)}(s) = \lim_{s\to 4^+} r^{(3)}(s) \Rightarrow 53760a_{73} + 7680a_{63} + 960a_{53} + 96a_{43} + 6a_{33} = 53760a_{74} + 7680a_{64} + 960a_{54} + 96a_{44} + 6a_{34}, \tag{27}$$

$$\lim_{s\to 5^-} r^{(3)}(s) = \lim_{s\to 5^+} r^{(3)}(s) \Rightarrow 131250a_{74} + 15000a_{64} + 1500a_{54} + 120a_{44} + 6a_{34} = 0, \tag{28}$$

$$\lim_{s\to 1^-} r^{(4)}(s) = \lim_{s\to 1^+} r^{(4)}(s) \Rightarrow 840a_{70} + 360a_{60} + 120a_{50} + 24a_{40} = 840a_{71} + 360a_{61} + 120a_{51} + 24a_{41}, \tag{29}$$

$$\lim_{s\to 2^-} r^{(4)}(s) = \lim_{s\to 2^+} r^{(4)}(s) \Rightarrow 6720a_{71} + 1440a_{61} + 240a_{51} + 24a_{41} = 6720a_{72} + 1440a_{62} + 240a_{52} + 24a_{42}, \tag{30}$$

$$\lim_{s\to 3^-} r^{(4)}(s) = \lim_{s\to 3^+} r^{(4)}(s) \Rightarrow 22680a_{72} + 3240a_{62} + 360a_{52} + 24a_{42} = 22680a_{73} + 3240a_{63} + 360a_{53} + 24a_{43}, \tag{31}$$

$$\lim_{s\to 4^-} r^{(4)}(s) = \lim_{s\to 4^+} r^{(4)}(s) \Rightarrow 53760a_{73} + 5760a_{63} + 480a_{53} + 24a_{43} = 53760a_{74} + 5760a_{64} + 480a_{54} + 24a_{44}, \tag{32}$$

$$\lim_{s\to 5^-} r^{(4)}(s) = \lim_{s\to 5^+} r^{(4)}(s) \Rightarrow 105000a_{74} + 9000a_{64} + 600a_{54} + 24a_{44} = 0, \tag{33}$$

$$r^{(5)}(0) = 0 \Rightarrow a_{50} = 0 \tag{34}$$

$$\lim_{s\to 1^-} r^{(5)}(s) = \lim_{s\to 1^+} r^{(5)}(s) \Rightarrow 2520a_{70} + 720a_{60} + 120a_{50} = 2520a_{71} + 720a_{61} + 120a_{51}, \tag{35}$$

$$\lim_{s\to 2^-} r^{(5)}(s) = \lim_{s\to 2^+} r^{(5)}(s) \Rightarrow 10080a_{71} + 1440a_{61} + 120a_{51} = 10080a_{72} + 1440a_{62} + 120a_{52}, \tag{36}$$

$$\lim_{s\to 3^-} r^{(5)}(s) = \lim_{s\to 3^+} r^{(5)}(s) \Rightarrow 22680a_{72} + 2160a_{62} + 120a_{52} = 22680a_{73} + 2160a_{63} + 120a_{53}, \tag{37}$$

$$\lim_{s\to 4^-} r^{(5)}(s) = \lim_{s\to 4^+} r^{(5)}(s) \Rightarrow 40320a_{73} + 2880a_{63} + 120a_{53} = 40320a_{74} + 2880a_{64} + 120a_{54}, \tag{38}$$

$$\lim_{s\to 5^-} r^{(5)}(s) = \lim_{s\to 5^+} r^{(5)}(s) \Rightarrow 63000a_{74} + 3600a_{64} + 120a_{54} = 0, \tag{39}$$

A system of linear equations was formed from Eqs. (2)–(39). The system consists of 38 equations with 40 unknowns; therefore, two variables can be chosen as independent parameters. These variables are defined as ($a_{73} = \alpha$) and ($a_{74} = \beta$). The solutions of the system, i.e., the coefficients of the 2P kernel defined by Eq. (1), are given in Table 1.

Table 1 The 40 coefficients of the polynomial seventh-order 2P kernel as functions of α and β

i	a_{7i}	a_{6i}	a_{5i}	a_{4i}
0	$245\alpha - 13909\beta + 821/1734$	$-621\alpha + 35289\beta - 1148/867$	0	$760\alpha - 43280\beta + 1960/867$
1	$301\alpha - 16855\beta + 1687/6936$	$-3309\alpha + 185593\beta - 2492/867$	$14952\alpha - 839958\beta + 32683/2312$	$-35640\alpha + 2005060\beta - 128695/3468$
2	$57\alpha - 2947\beta + 35/6936$	$-1083\alpha + 56295\beta - 175/1734$	$8736\alpha - 456654\beta + 1995/2312$	$-38720\alpha + 2035660\beta - 4725/1156$
3	α	$-27\alpha + 57\beta$	$312\alpha - 1353\beta$	$-2000\alpha + 13360\beta$
4	β	-34β	495β	-4000β
	a_{3i}	a_{2i}	a_{1i}	a_{0i}
0	0	$-384\alpha + 21900\beta - 1393/578$	0	1

1	$47880\alpha - 2696750\beta + 127575/2312$	$-36000\alpha + 2028996\beta - 13006/289$	$14168\alpha - 798714\beta + 120407/6936$	$-2352\alpha + 132628\beta - 2233/1156$
2	$101640\alpha - 5374510\beta + 1575/136$	$-157632\alpha + 8382180\beta - 5670/289$	$133336\alpha - 7127418\beta + 42525/2312$	$-47280\alpha + 2538900\beta - 8505/1156$
3	$7680\alpha - 70225\beta$	$-17664\alpha + 207174\beta$	$22528\alpha - 325119\beta$	$-12288\alpha + 211932\beta$
4	19375β	-56250β	90625β	-62500β

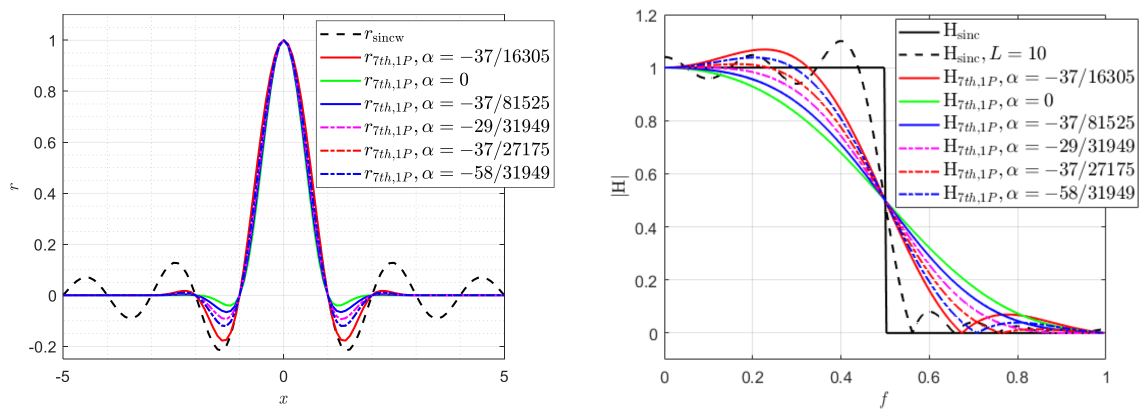
III. ANALYSIS OF THE TIME-DOMAIN AND AMPLITUDE CHARACTERISTICS

The influence of the kernel parameters on the time-domain and amplitude characteristics is first illustrated for the seventh-order 1P kernel. Fig. 1.a shows the time-domain characteristics of $r_{7th,1P}$ for $\alpha = \{-37/16305, 0, -37/81525, -29/31949, -37/27175, -58/31949\}$, together with the windowed ideal kernel r_{sincw} truncated to a length of $L = 10$. Fig. 1.b shows the amplitude characteristics of the ideal sinc kernel H_{sinc}, the windowed ideal kernel H_{sincw}, and the seventh-order 1P kernel $\mathrm{H}_{7th,1P}$.

The influence of the second parameter β is then analyzed for the seventh-order 2P kernel. Fig. 2.a shows the time-domain characteristics of $r_{7th,2P}$, with the parameter α fixed at $\alpha = -37/16305$. The effect of β is examined for six discrete values, $\beta = \{0, -2 \times 10^{-6}, -4 \times 10^{-6}, -6 \times 10^{-6}, -8 \times 10^{-6}, -10^{-5}\}$. Fig. 2.b shows the corresponding amplitude characteristics of the 2P kernel $H_{7th,2P}$.

Analysis of the time-domain and amplitude characteristics shows that variations in α for the 1P kernel, as well as variations in α and β for the 2P kernel, modify the shape of both characteristics. Variation of the parameter β provides an additional degree of freedom for finer adjustment of the 2P kernel characteristics. Therefore, the kernel parameters α and β can be optimized to adapt the interpolation kernel to a specific application.

Further work will focus on optimizing the seventh-order 2P interpolation kernel in the time domain, with the aim of increasing its similarity to the ideal sinc kernel, equalizing the slopes at the interpolation nodes, and ensuring the continuity of the $(n-1)$th derivative.



a) b)

Fig. 1. Characteristics of the windowed sinc kernel and the seventh-order 1P kernel for selected values of the parameter α: a) time-domain characteristics (r_{sincw}, $r_{7th,1P}$) and b) amplitude characteristics (H_{sincw}, $\mathrm{H}_{7th,1P}$).

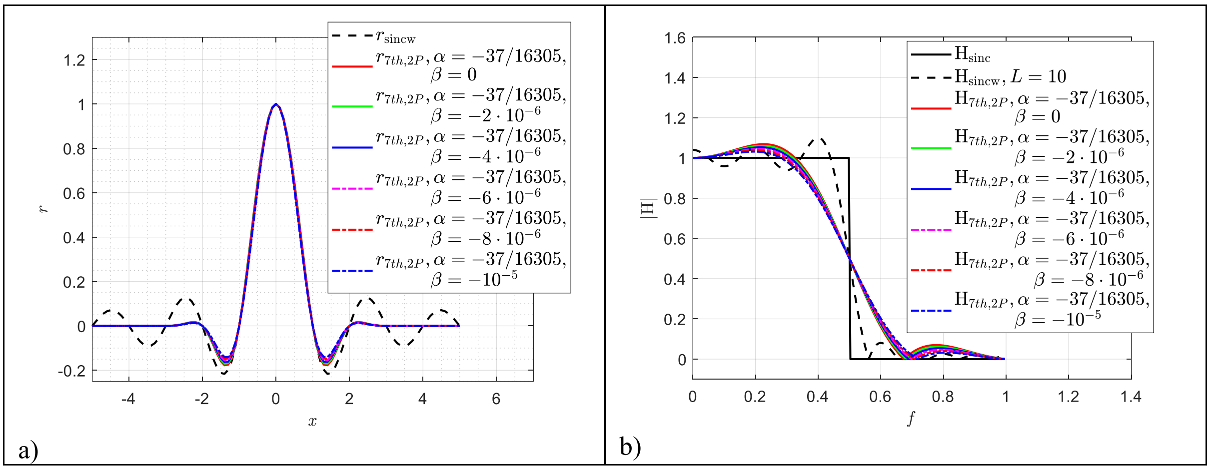


Fig. 2. Characteristics of the windowed sinc kernel and the seventh-order 2P kernel for selected values of the parameters α and β: (a) time-domain characteristics (r_{sincw}, $r_{7th,2P}$) and (b) amplitude characteristics ($\mathrm{H}_{\mathrm{sincw}}$, $\mathrm{H}_{7th,2P}$).

IV. CONCLUSION

In this paper, a polynomial seventh-order two-parameter (2P) interpolation kernel was constructed and parameterized. The kernel was developed by extending the seventh-order one-parameter (1P) interpolation kernel and imposing the required constraints at the interpolation nodes. A system of 38 linear equations with 40 unknown coefficients was formed, and two independent coefficients were introduced as the kernel parameters α and β. The resulting 40 polynomial coefficients were expressed as functions of these two parameters, providing a parameterized form of the seventh-order 2P interpolation kernel.

The analysis of the time-domain and amplitude characteristics demonstrated that the parameters α and β significantly affect the shape of the interpolation kernel and its spectral response. Compared with the 1P kernel, the introduction of the second parameter β provides an additional degree of freedom for adjusting the kernel characteristics. This enables finer control of the kernel shape and provides a basis for adapting the interpolation kernel to specific signal processing applications.

The proposed parameterization establishes a foundation for further optimization of the seventh-order 2P interpolation kernel. Future work will focus on optimizing the parameters α and β in the time domain to increase the similarity of the kernel to the ideal sinc kernel, equalize the slopes at the interpolation nodes, and ensure continuity of the $(n-1)$th derivative. The optimized kernel will subsequently be evaluated in terms of interpolation accuracy and computational efficiency for applications in digital signal and image processing.

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