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# DISCRETE SINE TRANSFORM INTERPOLATION APPROACH TO DESIGN A FRACTIONAL ORDER DIFFERENTIATOR

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## ABSTRACT

*In this article, discrete sine transforms interpolation approach is presented for designing a digital fractional order differentiator i.e. (DST-II). First described the definition of fractional differentiation. Then, DST based interpolation method i.e. (DST-II) is applied to compute the fractional differentiation of a given digital signal to obtain the transfer function of proposed method i.e. fractional order digital differentiator by using index mapping method. Finally, some numerical problems show their effectiveness of the proposed DST-II method as compared to Radial Basis function and Improved design of digital fractional-order differentiators using fractional sample delay.*

## KEYWORDS

digital differentiator, fractional derivative, hanning window, discrete sine transform (DST-II).

## JEL CODES

C00, C60.

## INTRODUCTION

During the past several decades, fractional calculus has played an important role in various fields like fluid flow, automatic control, biomedical applications, electrical networks, electromagnetic theory and image processing [1]-[2]. Fractional dimension is used to measure some real-world data such as coastline, clouds dust in the air and network of neurons in the body [3]-[4], we aim out interest at the realization of digital fractional derivative, which named as digital fractional order differentiator (FOD). Because digital FOD can determine and estimate the more characteristic of a given digital signal than integral order differentiator (IOD), it has been being an especial and useful tool in many increasing application, such as fractional order controls, radar and sonar processing, nonlinear or chaos time series processing and forecasting, geological signal detecting and processing, image signal compress and processing etc. Fractional sample delay has become an important device in the applications of time adjustment in the digital receiver, antenna array processing, speech coding.

Synthesis, modeling of musical instrument, and comb filter design etc [5]-[6]. The integer order n of derivative $D^v f(x)$ = ($d^n f(x) / dx^n$) of function is generalized to fractional order $D^v f(x)$, where v is a real number. One of the important research topics in fractional calculus is to implement the fractional operator $D^v$ in continuous and discrete time domain for continuous-time case, some methods for obtaining an approximated rational function using evaluation, interpolation and curve fitting techniques have been studied. These methods include Carlson's method, Roy's method, Charle 's method and Oustaloup's method. For the discrete -time case, there have been several methods presented to design finite-impulse-response (FIR) and infinite-impulse-response (IIR) filters for implementing operator $D^v$, including fractional differencing formula or Euler method, Tustin method, continued fraction method, least square method and Prony's method, continued fraction method [7], fractional sample delay method [8] and radial basis function [9].

On the other hand, the Discrete Sine Transform (DST) which is known to be statistically optimal performance with Karhunen-Loeve transform for highly correlated signal [10]. Until now, DST has been successfully applied to transform domain adaptive filtering [11], signal interpolation [12], image coding and compression [13], speech enhancement [14], image encryption [15].

In this paper, we will use one of the best interpolation method DST-II and Grunwald-Letnikov fractional derivative to design fractional order digital differentiator. In section II, the definitions of fractional derivative will be discussed in briefly. In Section III, the interpolation type of DST method i.e.(DST-II) is applied to design the fractional order digital differentiator. In section IV comparison result are presented. Finally, the conclusion is made.

**FRACTIONAL DIFFERENTIATION**

There are several definitions for fractional integral and fractional derivative to obtain the transfer function of the fractional order differentiator such as the Riemann-Liouville, the Grunwald-Letnikov and Caputo definitions. But in this paper we will use the Grunwald - Letnikov definition which is given by

$$c_k^v = \frac{\gamma(v+1)}{\gamma(k+1)\gamma(n-k+1)}$$

$$D^v f(x) = \lim_{h\to 0} \sum_{k=0}^{\omega} \frac{(-1)^k}{h^v} c_k^v f(x-kh) \tag{1}$$

The above notation (:) is gamma function. Based on this definition, the fractional derivative of exponential and sinusoidal signals are given by

$$D^v e^{ax} = a^v e^{ax} \tag{2}$$

$$D^v A\sin(\omega t + \varphi) = A\omega^v \sin\left(\omega t + \varphi + \frac{\pi v}{2}\right) \tag{3}$$

$$D^v A\cos(\omega t + \varphi) = A\omega^v \cos\left(\omega t + \varphi + \frac{\pi v}{2}\right) \tag{4}$$

The definition of fractional derivative has been described.

**DESIGN METHOD USING DST-II**

There are several types of discrete sine transform, namely DST-1, DST-II, DST-III, DST-IV. In this section the DST-II is presented. The continuous signal x(t) are sampled in the the discrete-time sequence x(0),x(1),..., x(N-1). Firstly, we will study how to compute the fractional order differentiation $D^v$ x(t) using the DST-II method. The DST-II is defined as

$$X(k) = \sqrt{\frac{2}{N}} \sum_{n=0}^{N-1} x(n)\, c_k \sin\left(\frac{(n+0.5)(k+1)\pi}{N}\right) \tag{5}$$

$$x(n) = \sqrt{\frac{2}{N}} \sum_{k=0}^{N-1} X(k)\, c_k \sin\left(\frac{(n+0.5)(k+1)\pi}{N}\right) \tag{6}$$

Substituting forward DST-II in equation (5) and into inverse DST-II in equation (6),
we get

$$c_k = \begin{cases} \frac{1}{\sqrt{2}} & k = N-1 \\ 1 & otherwise \end{cases}$$

$$x(n) = \sqrt{\frac{2}{N}} \sum_{k=0}^{N-1} \left[ \sqrt{\frac{2}{N}} \sum_{m=0}^{N-1} x(m)\, c_k^2 \sin\left(\frac{(m+0.5)(k+1)\pi}{N}\right)\right] \sin\left(\frac{(n+0.5)(k+1)\pi}{N}\right) \tag{7}$$

$$x(n) = \sum_{m=0}^{N-1} x(m)\, c_k^2 \left[\frac{2}{N} \sum_{k=0}^{N-1} \sin\left(\frac{(m+0.5)(k+1)\pi}{N}\right) \sin\left(\frac{(n+0.5)(k+1)\pi}{N}\right)\right]$$

$$x(t) = \sum_{m=0}^{N-1} x(m)\, b(m,t) \tag{8}$$

The interpolation basis function is given by

$$b(m,t) = \frac{2}{N} \sum_{k=0}^{N-1} \sin\left(\frac{(m+0.5)(k+1)\pi}{N}\right) \sin\left(\frac{(t+0.5)(k+1)\pi}{N}\right) \tag{9}$$

Taking the $v^{th}$ order fractional differentiation at both sides of equation (8)

$$D^v x(t) = \sum_{m=0}^{N-1} x(m)[D^v b(m,t)] \tag{10}$$

Using Linear property of fractional differentiation

$$[D^v b(m,t)] = \frac{2}{N} \sum_{k=0}^{N-1} \left(\frac{(k+1)\pi}{N}\right)^v \sin\left(\frac{(m+0.5)(k+1)\pi}{N}\right) \sin\left(\frac{(t+0.5)(k+1)\pi}{N} + \frac{\pi v}{2}\right) \tag{11}$$

Substitute the equation 11 into the equation 10 given below:

$$x(t) = \sum_{m=0}^{N-1} x(m)\, P_m(t) \tag{12}$$

$$P_m(t) = \frac{2}{N}\sum_{k=0}^{N-1}\left(\frac{(k+1)\pi}{N}\right)^v sin\left(\frac{(m+0.5)(k+1)\pi}{N}\right)sin\left(\frac{(t+0.5)(k+1)\pi}{N}+\frac{\pi v}{2}\right) \quad (13)$$

To obtain transfer function of fractional order digital differentiator that approximate the following Ideal frequency response is given below :

$$H_d(\omega) = (j\omega)^v e^{-j\omega I} \quad (14)$$

Where *I* represent delay values. The transfer function of the FIR filter is given as:

$$H(z) = \sum_{r=0}^{N-1} h(r)z^{-r} \quad (15)$$

After integer delayed samples the output will be

$$y(n) = \sum_{r=0}^{N-1} h(r)s(n \quad r) \quad (16)$$

Now a problem is that how we can determine the filter coefficient h(r) from the equation (12), such that the filter output y(n) is almost equal to the delayed fractional differentiation $D^v = s(N - I)$, that is

$$y(n) \approx D^v s(N-I) \quad (17)$$

Index mapping technique can be used to solve task, if

$$s(n) - x(N-1)$$
$$s(N-1) = x(N-2)$$
$$s(n-N+1) = x(0) \quad (18)$$

After link the equation (12) and (16), equation (18) can be written as

$$x(m) = s(n-(N-1)+m) \quad 0 < m < N-1 \quad (19)$$

Putting the values of $x(t) = s(n-(N-1)+t)$ into equation (12), we get

$$D^v s(n-(N-1)+t) = \sum_{m=0}^{N-1} s(n-(N-1)+m)P_m(t) \quad (20)$$

$$h(r) = P_{N-1-r}(N-1-I) \quad (21)$$

Substituting equation (13) into (21), then the filter coefficient will be

$$h(r) = \frac{2}{N}\sum_{k=0}^{N-1}\left(\frac{(k+1)\pi}{N}\right)^v sin\left(\frac{(N-r-0.5)(k+1)\pi}{N}\right)sin\left(\frac{(N-I-0.5)(k+1)\pi}{N}+\frac{\pi v}{2}\right) \quad (22)$$

We can modify the filter coefficient by using the optimization techniques and window techniques.
The Hanning window transfer function is given below

$$w(r) = 0.5 - 0.5 * \cos((2*\pi*r)/(N-1)) \quad (23)$$

So the modified filter coefficients can have determined by

$$h_w(r) = h(r)w(r) \quad (24)$$

To evaluate the performance of the DST-II, the integral square error of frequency response

$$E = \sqrt{\int_0^{\lambda\pi} |H(e^{j\omega}) - H_d(\omega)|^2 \, d\omega} \quad (25)$$

If the error E is smaller, then the performance of the design method will be better.

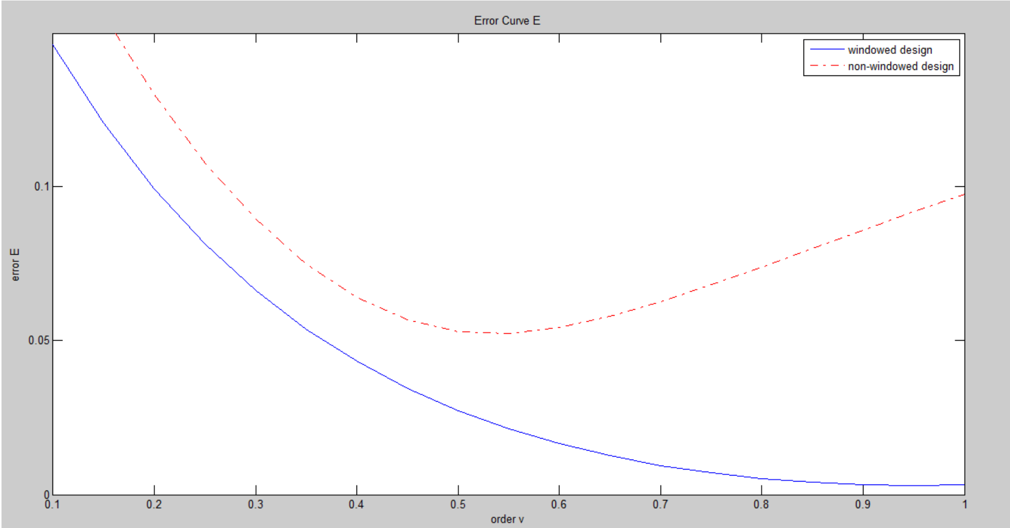
**Design Examples**

To evaluate the performance of the DST-II, the integral square error of frequency response is defined as

$$E = \sqrt{\int_0^{\lambda\pi} |H(e^{j\omega}) - H_d(\omega)|^2 \, d\omega} \quad (26)$$

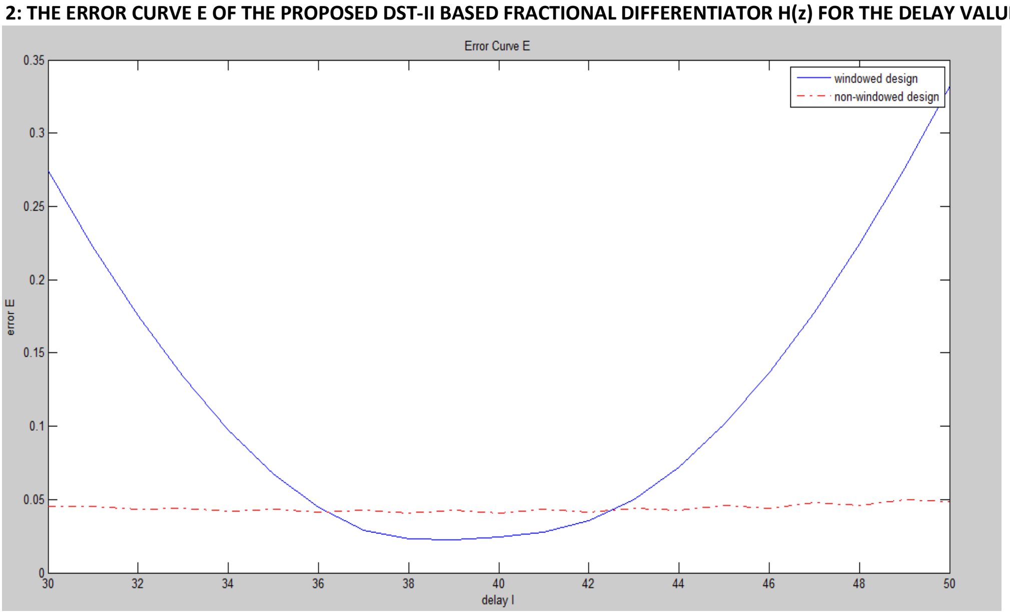
If the error E is smaller, then the performance of the design method will be better. ***Example 1:*** In this example, we will study the relation between the error E and for the DST-II method and. The design parameters are chosen as N = 80, I = 40, v = 0:2, and = 0:9. Moreover, Fig.1 shows the error curve E of the proposed DST-II based fractional order differentiator for the windowed and non-windowed function. In this figure, it can be seen that the windowed design error is minimum than the non-windowed design for the orders.

FIG. 1: THE ERROR CURVE E OF THE PROPOSED DCT-IV BASED FRACTIONAL DIFFERENTIATOR H(z) FOR ORDERS v



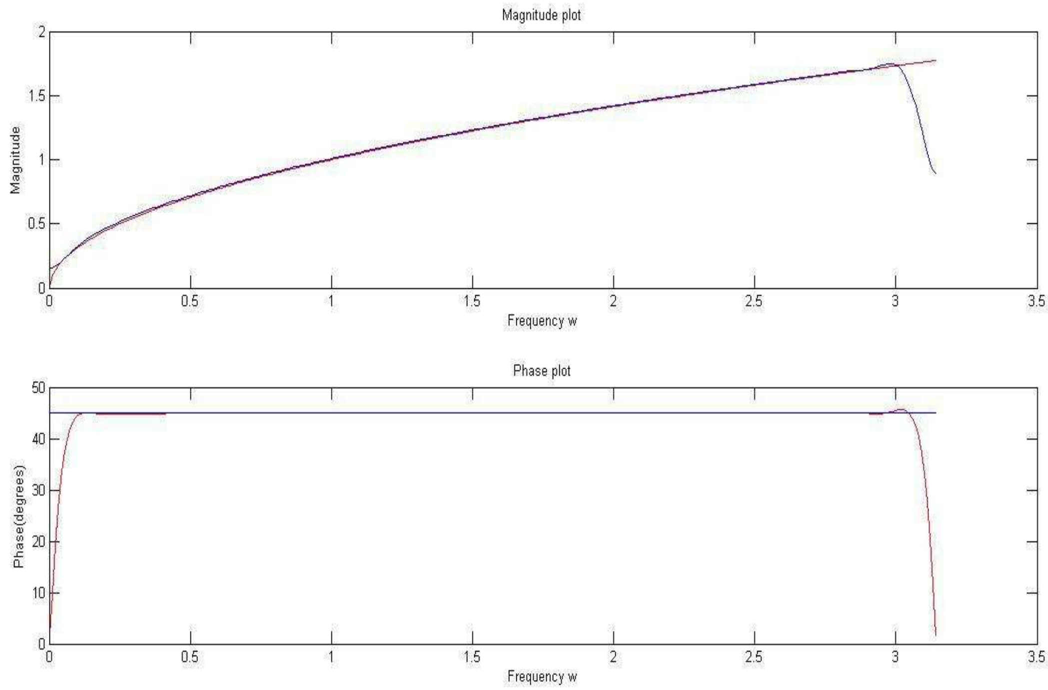

***Example 2***: In this example, we will study the relation between the error E and delay value I for the DST-II method and The design parameters are chosen as N = 80, I = 40, v = 0:2, and = 0:9. Moreover, Fig.2 shows the error curve E of the proposed DST-II based fractional order differentiator for the windowed and non-windowed function. The value of E is minimum at I = 20.

FIG. 2: THE ERROR CURVE E OF THE PROPOSED DST-II BASED FRACTIONAL DIFFERENTIATOR H(z) FOR THE DELAY VALUES I




***Example 3***: In this example, we will study the study the magnitude and phase response for the DST-II.
The design parameters are chosen as N = 80, I = 40 and = 0:9. Moreover, Fig.3 (a), (b) show the magnitude and phase responses (solid line) for the DST-II and order v = 0:5. In Fig.3(a) the dashed line show the ideal magnitude response $w^v$. Fig.3 (b) show the phase response 90 [angle ($B(e^{jw})$) + w*I ] = 0:5. In Fig.3 (b) the dashed line shows the ideal response 90v.

**FIG. 3: THE DESIGNED RESULTS OF THE WINDOWED DST-II BASED DIGITAL FRACTIONAL ORDER DIFFERENTIATOR H(z) FOR v = 0:5. (a) MAGNITUDE RESPONSE. (b) PHASE RESPONSE. THE DASHED LINE SHOW IDEAL RESPONSE**




## COMPARISON AND DISCUSSION

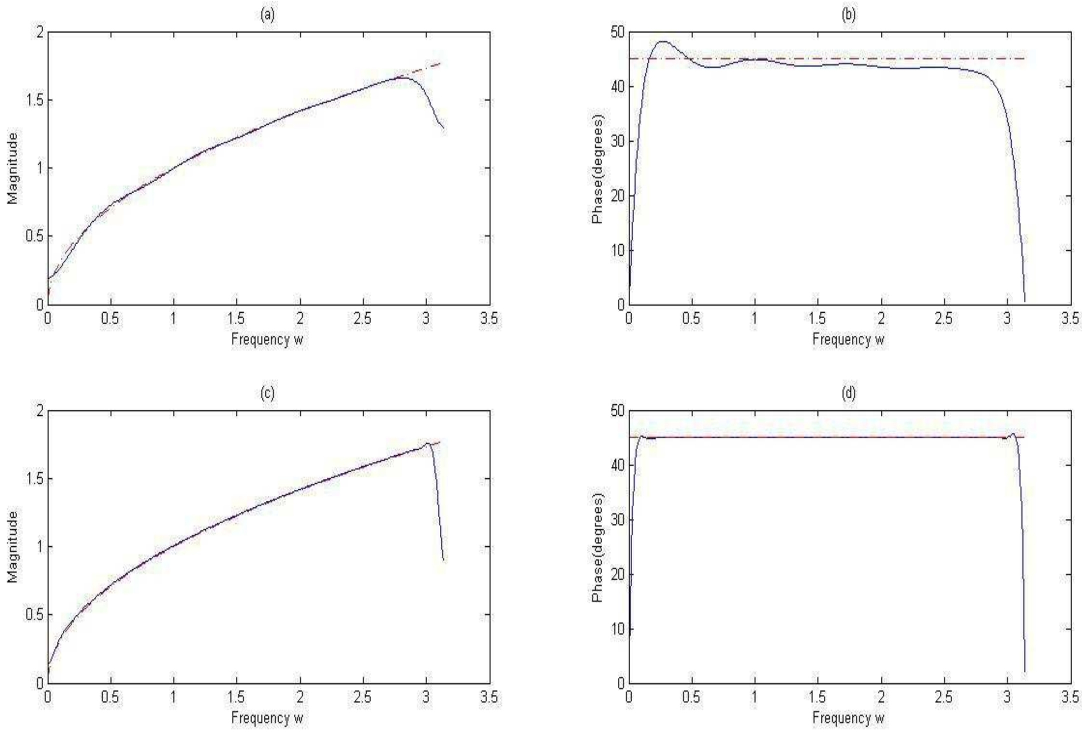
In this section, we will compare the result of DCT-IV with the Radial Basis Function [9] and Fractional Sample Method [8].

A. ***Comparison with Conventional Method***

Here, let us compare the proposed method DST-II with the conventional method (Radial Basis Function in [8]).

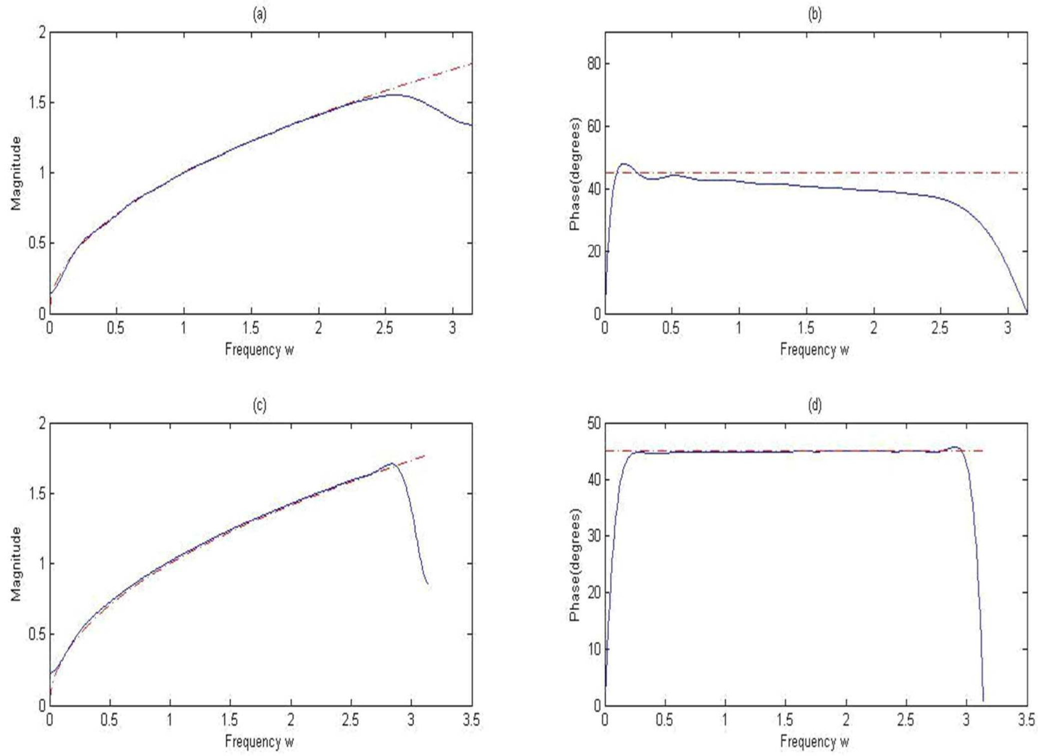
The parameters values are chosen as N = 100, I = 50 and v = 0:5. Fig. 4(a) and 4(b) show the magnitude and phase response of Radial Basis Function. 4(c) and 4(d) show the magnitude and phase response of Discrete Sine Transform (DST-II) using windowed. if $\lambda$ = 0.9 is chosen then the error E of the RBF method is 0.0356 and using the the DST-II method comes 0.012. Thus the proposed method has smaller design error as compare with the conventional method.

**FIG. 4: THE DESIGNED RESULTS (SOLID LINE) OF THE RADIAL BASIS FUNCTION METHOD IN [9]. (a), (b) THE RESULTS OF THE RADIAL BASIS FUNCTION (RBF) METHOD IN [9].(c),(d) THE RESULTS OF THE PROPOSED METHOD (DST-II). THE DASHED LINE SHOW THE IDEAL RESPONSE**



**B**. Here, let us compare the proposed method DCT-IV with the conventional method (Radial Basis Function in [8]). The parameters values are chosen as N = 40, I = 20 and v = 0:5. Fig. 5(a) and 5(b) show the magnitude and phase response of Radial Basis Function. 5(c) and 5(d) show the magnitude and phase response of Discrete Sine Transform (DST-II) using windowed. if $\lambda$ = 0:9 is chosen then the error E of the RBF method is 0.287 and using the the DST-II method comes 0.012. Thus the proposed method has smaller design error as compare with the conventional method.

**FIG. 5: THE DESIGNED RESULTS (SOLID LINE) OF THE FRACTIONAL ORDER FIR DIFFERENTIATOR. (a), (b) THE RESULTS OF THE FRACTIONAL DELAY METHOD IN [8].(c),(d) THE RESULTS OF THE PROPOSED METHOD (DST-II). THE DASHED LINE SHOW THE IDEAL RESPONSE**




## 5. CONCLUSION

In this article, discrete sine transforms interpolation approach are presented for designing a digital fractional order differentiator i.e. (DST-II). Then DST-II is applied to compute the fractional differentiation of a given digital signal to obtain the transfer function of proposed method i.e. fractional order digital differentiator by using index mapping method. Finally, some numerical problems show their effectiveness of the proposed DST-II method as compared to Radial Basis function and Improved design of digital fractional-order differentiators using fractional sample delay. However, 1-D has been studied in this paper. Thus, it is interesting to extend the proposed DST-II method to design the 2-D fractional order differentiator, Hilbert transform and other Optimization method in the future.

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