[illegible]

[illegible], *Member, IEEE*

***Abstract*— We propose an ultrasound speckle filtering method for not only preserving various edge features but also filtering tissue-dependent complex speckle noises in ultrasound images. The key idea is to detect these various edges using a phase congruence-based edge significance measure called phase asymmetry (PAS), which is invariant to the intensity amplitude of edges and takes 0 in non-edge smooth regions and 1 at the idea step edge, while also taking intermediate values at slowly varying ramp edges. By leveraging the PAS metric in designing weighting coefficients to maintain a balance between fractional-order anisotropic diffusion and total variation (TV) filters in TV cost function, we propose a new fractional TV framework to not only achieve the best despeckling performance with ramp edge preservation but also reduce the staircase effect produced by integral-order filters. Then, we exploit the PAS metric in designing a new fractional-order diffusion coefficient to properly preserve low-contrast edges in diffusion filtering. Finally, different from fixed fractional-order diffusion filters, an adaptive fractional order is introduced based on the PAS metric to enhance various weak edges in the spatially transitional areas between objects. The proposed fractional TV model is minimized using the gradient descent method to obtain the final denoised image. The experimental results and real application of ultrasound breast image segmentation show that the proposed method outperforms other state-of-the-art ultrasound despeckling filters for both speckle reduction and feature preservation in terms of visual evaluation and quantitative indices. The best scores on feature similarity indices have achieved 0.867, 0.844 and 0.834 under three different levels of noise, while the best breast ultrasound segmentation accuracy in terms of the mean and median dice similarity coefficient are 96.25% and 96.15%, respectively.**

***Index Terms*— Ultrasound despeckling, speckle noise, fractional-order diffusion filter, fractional-order TV filter, edge detection, phase congruency, phase asymmetry, image denoising.**

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[illegible] 200240, [illegible]

[illegible] 200233, [illegible]

[illegible], TX 75080 USA.

[illegible]

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I. Introduction

CURRENT [illegible] [1], [2] [illegible] [3], [4] [illegible] [5], [6] [illegible] [5]–[7]. [illegible] [8], [illegible] [7]. [illegible] [9] [illegible] 3D [illegible] 2D [illegible] [10]. [illegible]

[illegible] [11]. [illegible] [13], [14] [illegible]

[illegible] (NLM) [illegible] [14] [illegible]

[15] ... In ... C ... *et al.* [16] ... M ... (SBF) [17] ... H ... T NLM ... NLM ... C ... *et al.* [18] ... NLM (OBNLM) ... An ... OBNLM ... Z ... *et al.* [19] ... R ... Z ... *et al.* [20] ... (NLLRF) ... H ... NLM ... [21].

In ... P ... M ... (AD) ... [22], ... (SRAD) [23] ... (DPAD) [24] ... AD ... T SRAD ... DPAD ... T ... [25] ... U ... C ... *et al.* [16] ... U ... [26] ... [27] ... H ... M ... T ... B ... F ... [28] ... AD (FAD) ... N ... R ... F ... *et al.* [8] ... (ADLG) ... H ... ADLG ... B ... AD ...

[29] ... [30] ... AD ... H ...

E ... T ... A ... [31]. T ... T ... [32] ... O ... *et al.* [33] ... H ... [2] ... C ... *et al.* [34] ... S ... [35], ... [36], ... [37], [38], ... H ...

T ... [39], [40] ... In ... M ... M ... *et al.* [41], [42]. T ... F ... A ... T ... M ... T ... M ... -P ... N ... [43]. W ... [44] ... (PC)- ... (PS) ... (PAS, ... T ... I) ...

. In . A (AM-FM) [48] [50] [51], [40] [52]. [53] 2D f R . f_M : $f_M = (f, f_R) = (f, r_1 * f, r_2 * f)$, f_R R f, $r_1(x_1, x_2)$ $r_2(x_1, x_2)$ R :

$$r_1(x_1, x_2) = \frac{-x_1}{2\pi \left(x_1^2 + x_2^2\right)^{3/2}}$$

$$r_2(x_1, x_2) = \frac{-x_2}{2\pi \left(x_1^2 + x_2^2\right)^{3/2}} \tag{1}$$

f_M b. f_M $f_M = (b * f, b * r_1 * f, b * r_2 * f) = (e_s, o_s)$, e_s o_s . b e_s o_s; C C F [54]. In 2D C :

$$C(w) = n_c \, |w|^a \, (-s\,|w|)\,, a \geq 1 \tag{2}$$

$w = (w_1, w_2)$, s , $n_c = \left(\frac{\pi\, 4^{a+1}\, s^{2a+1}}{\Gamma(2a+1)}\right)^{\frac{1}{2}}$, $\Gamma(\cdot)$, a . W $a = 1.58$, [39]. T , K [44] PAS . T , - PAS :

$$PA = \sum_s \frac{\lfloor |o_s| - |e_s| - T_s \rfloor}{\sqrt{e_s^2 + o_s^2} + \varepsilon} \tag{3}$$

PA PAS , ε , T_s - , $\lfloor \cdot \rfloor$, s C . S , s s ( ) n.

F . 1 PAS . W PAS $s = 5$ $s = 10$. T PAS $s = 20$ $s = 25$. T PAS $s = 15$. T , $s = 15$.

F . 1. E PAS . ( ) T n; PAS : ( ) $s = 5$, ( ) $s = 10$, ( ) $s = 15$, ( ) $s = 20$, ( ) $s = 25$.

PAS . T PAS 0 1, 0 (-) 1 ( ) . In . A PAS . D PAS , - . F PAS 1.

B. Fractional-Order Differential

T - - [47]. F $f(x) \in L^2(R)$, - :

$$D^\alpha f(x) = \frac{d^\alpha f(x)}{d x^\alpha} \tag{4}$$

α . T F $D^\alpha f(x)$:

$$\begin{aligned} D^\alpha f(x) \overset{FT}{\Leftrightarrow} (\hat{D}^\alpha f)(w) &= (iw)^\alpha \hat{f}(w) \\ &= |w|^\alpha \left[i\,\theta^\alpha(w)\right] \hat{f}(w) \\ &= |w|^\alpha \left[\frac{\alpha\pi i}{2}\, n(w)\right] \hat{f}(w) \end{aligned} \tag{5}$$

w , n$(\cdot)$, $(iw)^\alpha = |w|^\alpha \left[\frac{\alpha\pi i}{2}\, n(w)\right]$. A - - α, F . 2. F F . 2, - $0 < w < 1$, . N $w > 1$, α . T - - .

D . A - -

[redacted] 2. T r -r n r r n r n r n r.

[redacted] r n r n r r r n n r r n n r n [47]. E n -r n r r n r -r n r r . T r n [46]. T r r r n r α n PAS r n . III-A r n n r n r n . C rr n , r r r n n n r -: C n n, Gr n -L n -L) n n n R nn-L (R-L) [55], [56]. G-L n n r n n n n n, G-L n n r n r n. A r n [57], α- r r r n n $f(x)$ n G-L :

$$D^{\alpha} f(x) \triangleq \lim_{h\to 0} \frac{1}{h^{\alpha}} \sum_{l=0}^{[\frac{d-c}{h}]} (-1)^{l} \binom{\alpha}{l} f(x-lh) \qquad (6)$$

[redacted] r α r n r r, $[c, d]$ r n $f(x)$, n r r $\frac{d-c}{h}$ $[\frac{d-c}{h}]$, n r $\binom{\alpha}{l}$ n n :

$$\binom{\alpha}{l} = \frac{\Gamma(\alpha+1)}{\Gamma(l+1)\Gamma(\alpha-l+1)} \qquad (7)$$

[redacted] r $\Gamma(n) = (n-1)!$ n n.

[redacted] Fractional-Order AD Filter and Fractional-Order [redacted] Filter

[redacted] T n n r n n n r -AD [22] r:

$$\frac{\partial u}{\partial t} = div\left[c\left(|\nabla u|\right) \cdot \nabla u\right], \qquad (8)$$

r div n n r r, $|\nabla u|$ ∇u, n $c(\cdot)$

[illegible] λ [illegible] λ [illegible] T [illegible] In [illegible] λ [illegible] PSNR [illegible] [60]. W [illegible] λ [illegible] 0.01 [illegible] R [illegible] PAS [illegible]:

$$\begin{cases} \varphi = (PA-1)^2 \\ \gamma = PA(2-PA) \end{cases} \tag{15}$$

[illegible] PA [illegible] PA [illegible] B [illegible] PA [illegible] 0, [illegible] FAD [illegible] W [illegible] PA [illegible] 1, [illegible] FTV [illegible] B [illegible] PA [illegible] 1, FAD [illegible].

H [illegible] FAD [illegible] T [illegible] PAS [illegible] T PAS [illegible] F [illegible] PAS [illegible] W [illegible] $f(|\nabla^{\alpha} u|)$ [illegible] $c(\cdot)$ [illegible] (12). T [illegible]:

$$c\left(\left|\nabla^{\alpha} u\right|, PA\right) = 1/\left[1+\frac{|\nabla^{\alpha} u|\cdot(1+254\cdot PA)}{k_1^2}\right] \tag{16}$$

[illegible] $k_1 = k_0 e^{-0.05(n_{iter}-1)}$ [illegible] k [illegible] (9). H [illegible] n_{iter} [illegible] k_0 [illegible].

G [illegible] A [illegible] S [illegible] II-B, [illegible] α [illegible] PAS [illegible] S [illegible] [46] [illegible]:

$$\alpha = 1 + \ \ _2\left(1+PA^2\right) \tag{17}$$

[illegible] PA [illegible] PAS [illegible] T [illegible] $\alpha \in (1,2)$. T [illegible] PFDTV [illegible].

In [illegible] PAS [illegible] A [illegible] PAS [illegible] A [illegible] (17), [illegible] PAS [illegible] α [illegible] T PFDTV [illegible].

B. Numerical Solver

W [illegible] E [illegible]-L[illegible] [61] [illegible] (14). A [illegible] u [illegible] $E(u)$ [illegible] $E(u)$ [illegible] In [illegible] u [illegible] W [illegible] 0, [illegible] 0. T [illegible] $\eta \in C^{\infty}(\Omega)$ [illegible] e. D [illegible]:

$$\begin{aligned} \Phi(e) &:= E(u+e\eta) \\ &= \int_{\Omega}\left[\varphi f\left(\left|\nabla^{\alpha}(u+e\eta)\right|\right) + \gamma\left|\nabla^{\alpha}(u+e\eta)\right|\right]dxdy \\ &\quad + \int_{\Omega}\left(\frac{\lambda}{2}|u+e\eta-u_0|^2\right)dxdy \end{aligned} \tag{18}$$

W [illegible] $\Phi(e)$ [illegible]:

$$\begin{aligned} \Phi'(e) &= \frac{d}{de}\Phi(e) \\ &= \varphi\int_{\Omega}\left(f'\left(\left|\nabla^{\alpha}(u+e\eta)\right|\right) \times\frac{\nabla_x^{\alpha}(u+e\eta)\nabla_x^{\alpha}\eta+\nabla_y^{\alpha}(u+e\eta)\nabla_y^{\alpha}\eta}{\sqrt{\left(\nabla_x^{\alpha}(u+e\eta)\right)^2+\left(\nabla_y^{\alpha}(u+e\eta)\right)^2}}\right)dxdy \\ &\quad +\gamma\int_{\Omega}\left(\frac{\nabla_x^{\alpha}(u+e\eta)\nabla_x^{\alpha}\eta+\nabla_y^{\alpha}(u+e\eta)\nabla_y^{\alpha}\eta}{\sqrt{\left(\nabla_x^{\alpha}(u+e\eta)\right)^2+\left(\nabla_y^{\alpha}(u+e\eta)\right)^2}}\right)dxdy \\ &\quad +\lambda\int_{\Omega}(u+e\eta-u_0)\eta dxdy, \end{aligned} \tag{19}$$

L [illegible] $e=0$, [illegible]:

$$\begin{aligned} &\Phi'(0) \\ &= \varphi\int_{\Omega}\left(c\left(\left|\nabla^{\alpha}u\right|^2, PA^2\right)\left(\nabla_x^{\alpha}u\,\nabla_x^{\alpha}\eta+\nabla_y^{\alpha}u\,\nabla_y^{\alpha}\eta\right)\right)dxdy \\ &\quad +\gamma\int_{\Omega}\frac{\nabla_x^{\alpha}u\,\nabla_x^{\alpha}\eta+\nabla_y^{\alpha}u\,\nabla_y^{\alpha}\eta}{|\nabla^{\alpha}u|}dxdy \\ &\quad +\lambda\int_{\Omega}(u-u_0)\eta dxdy \end{aligned} \tag{20}$$

[illegible] $|\nabla^{\alpha}u| = \sqrt{\left(\nabla_x^{\alpha}u\right)^2+\left(\nabla_y^{\alpha}u\right)^2}$. A [illegible] u, [illegible]

$\Phi'(0) = 0$. T … (20), … n … n … r … r … n … r …:

$$\nabla_x^\alpha u \, \nabla_x^\alpha \eta + \nabla_y^\alpha u \, \nabla_y^\alpha \eta = \left(\left(\nabla_x^\alpha\right)^* \nabla_x^\alpha u + \left(\nabla_y^\alpha\right)^* \nabla_y^\alpha u\right) \eta \tag{21}$$

… r $\left(\nabla_x^\alpha\right)^*$ … n $\left(\nabla_y^\alpha\right)^*$ … r … n … r … r … ∇_x^α … n ∇_y^α r … [62]. B … n … n … n … r … (20) …:

$$\begin{aligned}
&\Phi'(0) \\
&= \varphi \int_\Omega c\left(\left|\nabla^\alpha u\right|^2, PA^2\right)\left(\left(\nabla_x^\alpha\right)^* \nabla_x^\alpha u + \left(\nabla_y^\alpha\right)^* \nabla_y^\alpha u\right) \eta \, dy \\
&\quad + \gamma \int_\Omega \frac{\left(\nabla_x^\alpha\right)^* \nabla_x^\alpha u + \left(\nabla_y^\alpha\right)^* \nabla_y^\alpha u}{\left|\nabla^\alpha u\right|} \eta \, dy \\
&\quad + \lambda \int_\Omega \left(u - u_0\right) \eta \, dy
\end{aligned} \tag{22}$$

F r … $\eta \in C^\infty(\Omega)$, … E … r-L … r … n … n …:

$$\begin{aligned}
&\varphi c\left(\left|\nabla^\alpha u\right|^2, PA^2\right)\left(\left(\nabla_x^\alpha\right)^* \nabla_x^\alpha u + \left(\nabla_y^\alpha\right)^* \nabla_y^\alpha u\right) \\
&\qquad + \gamma \frac{\left(\nabla_x^\alpha\right)^* \nabla_x^\alpha u + \left(\nabla_y^\alpha\right)^* \nabla_y^\alpha u}{\left|\nabla^\alpha u\right|} + \lambda\left(u - u_0\right) = 0
\end{aligned} \tag{23}$$

… r u … n … n … n. … L ∇E … n … r … r … n … n $E(u)$; … n … r … n … n … r u … r … n … $E(u)$ … $\nabla E = 0$. T …, ∇E …:

$$\begin{aligned}
\nabla E = &\varphi c\left(\left|\nabla^\alpha u\right|^2, PA^2\right)\left(\left(\nabla_x^\alpha\right)^* \nabla_x^\alpha u + \left(\nabla_y^\alpha\right)^* \nabla_y^\alpha u\right) \\
&+ \gamma \frac{\left(\nabla_x^\alpha\right)^* \nabla_x^\alpha u + \left(\nabla_y^\alpha\right)^* \nabla_y^\alpha u}{\left|\nabla^\alpha u\right|} + \lambda\left(u - u_0\right)
\end{aligned} \tag{24}$$

T … r … u … r … n … n … n [63]. S … n r … n … r … r Δt … n … k … n … r … n $-\nabla E$, *i.e.*, $u^{n+1} = u^n + \Delta t(-\nabla E)$. F n …, … n … r … u … n … n … n $E(u)$.

C. Numerical Algorithm

T … (24) … n … r …, … G-L … r … n … r n … n … r … n … n. W … n … u … $X \times Y$, … r X … n Y … r … n … r … n … r … n … r … n … r … T n, … n … n … r … ∇^α, ∇_y^α, $\left(\nabla_x^\alpha\right)^*$ … n $\left(\nabla_y^\alpha\right)^*$, … n …:

$$\begin{cases}
\nabla_x^\alpha u_{i,j} = \displaystyle\sum_{l=0}^{j} (-1)^l \binom{\alpha}{l} u_{i,j-l} \\
\nabla_y^\alpha u_{i,j} = \displaystyle\sum_{l=0}^{i} (-1)^l \binom{\alpha}{l} u_{i-l,j}
\end{cases} \tag{25}$$

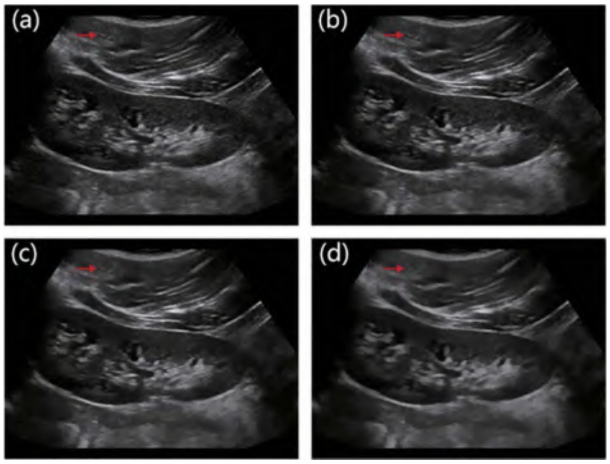
$$\begin{cases}
\left(\nabla_x^\alpha\right)^* u_{i,j} = \displaystyle\sum_{l=0}^{Y-1-j} (-1)^l \binom{\alpha}{l} u_{i,j+l} \\
\left(\nabla_y^\alpha\right)^* u_{i,j} = \displaystyle\sum_{l=0}^{X-1-i} (-1)^l \binom{\alpha}{l} u_{i+l,j}
\end{cases} \tag{26}$$

Algorithm 1 PFDTV F … r -Pr … r … n … D … k … F … r

Input:

TABLE II

COMPARISON OF THE PSNR, MSSIM AND FSIM VALUES AMONG DIFFERENT FILTERS



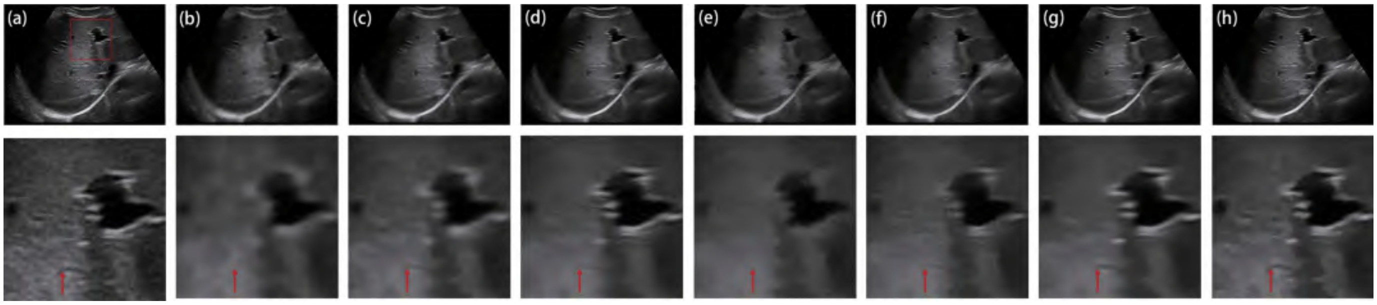
F 4. E k k_0. (a) T ... ; k r ( ) $k_0 = 5$, ( ) $k_0 = 20$, ( ) $k_0 = 100$.

r r n r r . T MSSIM r r n k r r n . T FSIM r r n PFDTV r r r r n r r r n.

B. Clinical Image Experiment

S n r r n r k n r r n r n r r n r n n r r n . T r r , r n n r n r r n PFDTV . T n r n r n r .[3]

T r r n r n n r n r r n n r r n r r r. T , PFDTV n . T r r n r : s, k_0 n n_{iter}. A r n n S n II-A, s 19( )-336T8( )3(AS104.5(C)1(S0.3199-171765TD.0043T [(2)5(n)8



F . 6. D k r ra n a r a a an rr n n a . (a) T r n a a ; r ( ) Fr , ( ) SRAD, ( ) OBNLM, ( ) SBF, ( ) ADLG, ( ) NLLRF, an ( ) **PFDTV**.

F . 7. D k r ra n a a an rr n n a . (a) T r n a a ; r ( ) Fr , ( ) SRAD, ( ) OBNLM, ( ) SBF, ( ) ADLG, ( ) NLLRF, an ( ) **PFDTV**.

r a k a r k r n. S a r , a r n n n a r arr n F . 7, PFDTV n n an n a n ra . SRAD, OBNLM an NLLRF r n ra n a . O r r r n a r k n . T r a a k a r n

F . 8. D k r ra n ROI (a). T n n ROI r (a) (b) OBNLM, ( ) SBF, ( ) ADLG, ( ) NLLRF, an ( ) **PFDTV**.

n an r , DSC an JS a- r n ra n an n r n an r n r . A an r n n , HD an HM an n r n an n r n an r n r . H n , a r n r a r DSC an JS, a a r HD an HM. Ta III an Ta IV an an an a DSC, JS, HD an HM r r n n r n k BUS , r . O , PFDTV a DSC an JS a , a HD an HM a , n a PFDTV a r n n r an r r .

T a n r OBNLM, NLLRF an PFDTV ar a r an ar n a r an In (R) C r (TM) CPU a 2.71 GH an 8 GB RAM. T a n r n F . 7(a) a 225×300 86.54 n . OBNLM n 2.85 n an n r NLLRF n 430.21 n . A PFDTV n

T

		HD	HM
In	5.02	16.9933	3.3599
Fros	8.02	9.8418	2.1265
SRAD		8.2271	1.5781
OBNLM	93.64	90.80	

(b) (c) (d)

PFDTV

SRAD, OBNLM, SBF, ADLG, NLLRF, **PFDTV**.

TABLE IV

DIAN DSC, JS, HD AND HM VALUES FOR DIFFERENT SEGMENTATION RESULTS ON TEN BREAST ULTRASOUND IMAGES

ACKNOWLEDGEMENT

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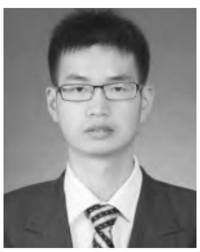

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