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Comparative Analysis of Warp-Chine and Wigley Shapes On Resistance Assessment of a Pentamaran

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ABSTRACT

This paper investigated the effect of the shape diversity of hulls and their positions to wave resistance, wave interference, and far-field wave patterns of a pentamaran. The investigations were using experimental and application of design tool based on Michell's thin ship theory on the various clearances and stagger. The models used a hard chine hull, typically for a planning ship that recommended by Savitsky, and another one, Wigley. Comparison of calculations and experimental was not satisfactory, especially at Fn below 0.5, possibly due to viscous factors were still influential at low speed where the theoretical incapable of predicting the valuable. Based on Michell calculation, the deviation of both wave and interference resistance between the two models was to 36.6%, 58.3%, respectively, with the warp-chine model had lower wave resistance than Wigley. The experimental results exhibited that the wave component of all models has decreased with rising of stagger at Fn> 0.5. The deviation in average between test and calculation of tool on wave resistance for Wigley of 8.25% and warp-chine by 11.8%. Furthermore, the differences of far-field wave patterns between two models had been illustrated by the computational tool on the sectoral patch of the aft of the ship

Keywords:
Pentamaran; wave resistance; wave pattern; wave interference

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1. Introduction

It has been recognised that the resistance problem of Multihull is complicated due to the interference effects between hull components other than the resistance factors from the shape of the hulls and the waves flow due to their movement. The addition of the wetted surface area of Multihull will automatically increase the frictional resistance. However, the wave resistance can be lowered by the appropriate shape and the proper placement of outriggers. The shape of the hull largely determines the speed of a ship due to it has a significant impact on the resistance and behaviour in a seaway.

The use of a slender hull is one of the solutions to increase the speed and problem solving of existing Multihull or high-speed craft [1]. The "slender" commonly used on Multihull ships is Wigley hull. Another form also widely used on Multihull to minimise resistance and high speed is warp-chine

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hull. Research of Tuck [2] and Moraes *et al.,* [3] had proved chine hull successfully to reduce resistance and had an excellent propulsive efficiency than Wigley hull.

At the end of the 1920s, Wigley and Weinblum had discovered Michell's integral of the linear theory of ship wave resistance. Tuck [4] worked on wave resistance based on Michell's thin ship theory and compared it with the experimental of Chapman [5]. Furthermore, Tuck *et al.,* [6, 7] delivered the slender-ship approximation as a generalisation of Michell's theory. In this work was using a design tool based on Michell's thin ship theory developed by Lazaukas [8] namely "Michlet" and validating with the experimental. This work was to investigations the hydrodynamic characteristics of wave resistance, wave interference, and far-field wave patterns with diversity hull: warp-chine, which its hull not pure thin and Wigley on several configurations of clearance and stagger.

2. Model Characteristic

The pentamaran as a trimaran formation was composed of one main hull and four outriggers, with two hulls model to be analysed, i.e. hard chine and Wigley. The hull plan of pentamaran warp-chine is shown in Figure 1 and Wigley in Figure 2, and the dimensional parameters are given in Table 1.

Table 1
Principal characteristics of model pentamaran

Main Dimension	Warp-chine		Wigley	
	Main hull	Side hull	Main hull	Side hull
LOA (m)	1.500	0.414	1.800	0.500
B (m)	0.150	0.030	0.180	0.050
T (m)	0.024	0.012	0.080	0.030
H (m)	0.090	0.078	0.170	0.116
WSA (m^2)	0.491	0.041	0.368	0.033
∇ (m^3)	$9.0x10^{-3}$	$3.210x10^{-4}$	81.772	1.775
Deadrise β (deg)	20	35	-	-

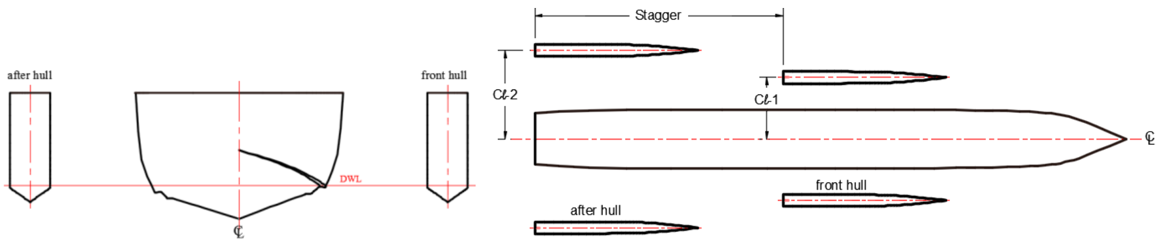

Fig. 1. Pentamaran warp-chine

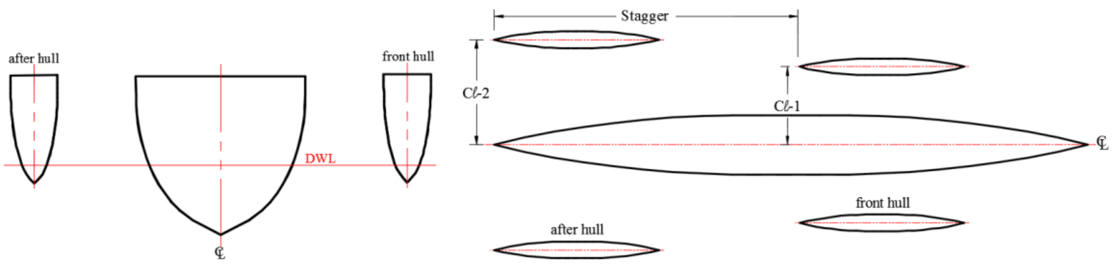

Fig. 2. Pentamaran Wigley

Stagger (ST) expresses the longitudinal position between side hulls as the distance from the transom section of the after hull to the transom section of the front hull. The transverse position, i.e. the clearance 1 (Cl-1) is the distance from the centerline of the front hull to the centerline plane of the main hull; while the clearance 2 (Cl-2) is the distance from the centerline of after hull to the centerline of the main hull. The stagger as a percentage of Length of waterline (Lwl) of main-hull. The clearance as a percentage of breadth moulded (Bml) of the main hull.

3. Experimental Test

3.1 Model Configuration

References of [9-13] had proved the interference effects with certain combinations of stagger, separation and speeds can significantly reduce the total wave resistance. And Yeung *et al.,* [13] suggested that a negative interference resistance could be a significant reduction of the wave-resistance system. In this work, the tests performed on pentamaran to prove the statement of them, which it's carried out on the clearance 1 (Cl1): 1.05 Bml, 1.2Bml; the clearance 2 (Cl2): 1.2Bml, 1.5 Bml; and the stagger: 0.35L, 0.42L, 0.5L. Total of tested were twelve pentamaran configurations in the speed range corresponding to Froude number, Fn 0.4 - 1.0. The warp-chine hulls were expressed as initials C1-C6 and Wigley hulls as initials W1-W6 had revealed in Table 2.

Table 2
Model test and configurations

Configuration	Stagger (m)	Cl -1 (m)	Cl -2 (m)
C1/ W1	0.36Lwl	1.20Bml	1.20Bml
C2/ W2	0.36Lwl	1.05Bml	1.50Bml
C3/ W3	0.42Lwl	1.20Bml	1.20Bml
C4/ W4	0.42Lwl	1.05Bml	1.50Bml
C5/ W5	0.50Lwl	1.20Bml	1.20Bml
C6/ W6	0.50Lwl	1.05Bml	1.50Bml

The model tests were conducted in the towing tank of Institut Teknologi Sepuluh Nopember which the dimensions are 50 m x 3 m x 2 m in length, width and depth. The hydrodynamic resistance in calm water, according to the ITTC 2002 regulations in a single test [14].

3.2 Resistance Assessment

Tuck *et al.,* [7] represent that Michell's thin-ship theory can be applied to Multihull, which the relative interaction error between the hulls was proportional to the beam-to-length ratio. Their investigation exhibited that "transverse" wave mostly at Fn 0.4, while the "diverging" wave dominant at Fn 1.0. The capturing of transverse and diverging as a realistic representation of a complete ship wave can be generated from the design tool from Lazaukas [8], "Michlet".

The wave resistance (Rw) based on Michell's theory by the integration of the free-wave spectrum as the energy left in the wave system is

$$R_W = \frac{2}{\pi}\rho U^2 k_0^4 \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} d\theta \, sec^2\theta \left| \iint_W dxdz Y(x,z) e^{ik_0 x \sec\theta + ik_0 z \sec^2\theta} \right|^2 \quad (1)$$

where y = ±Y (x, y), the hull surface which the (x, z) integral as the centerline *W* of the ship; *ρ*, the water density; *U*, the ship speed; $k_0 = g/U^2$, the wavenumber; and *g* for gravity. The integral in bar Eq (1) is the complex amplitude function A(θ) called free wave spectrum.

$$A(\theta) = -\frac{2i}{\pi} k_0^2 \sec^4\theta \iint Y(x,y) e^{(k_0 z \sec^2\theta + i k_0 x \sec^2\theta)}\, dxdz \quad (2)$$

The free-surface wave pattern z = ζ(x,y) of Multihull with N hulls generates amplitude on each hull (j), so the total far-field waves are

$$\varsigma(x,y) = \sum_{j=1}^{N} R_W \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} A_j e^{-ik(\theta)[(x-xj)\cos\theta + (z-zj)\sin\theta]}\, d\theta \quad (3)$$

$$= \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} e^{-ik(\theta)[x\cos\theta + y\sin\theta]} \sum_{j=1}^{N} A_j\, e^{ik(\theta)[xj\cos\theta + yj\sin\theta]} d\theta \quad (4)$$

where $k(\theta) = k_0 \sec^2\theta$; $A_j(\theta) = \sigma_j A_o(\theta)$ which σ_j, a fraction of Multihull total displacement. Then the combined wave amplitude is:

$$A(\theta) = A_o(\theta) F(\theta) \quad (5)$$

F(θ), wave interference is a factor of wave-making of each hull which determined by the value of $A_0(\theta)$.

$$F(\theta) = \sum_{j=1}^{N} \sigma j e^{ik(\theta)[xj\cos\theta + yj\sin\theta]} \quad (6)$$

Experimental is to validate the calculation based on Michell's theory in determining the total resistance (R_T) and form factor (k+1), which is determined by the Prohaska method to estimate the viscous component. The equation for the wave resistance (R_W) is obtained via the Hughes by Lunde *et al.,* [15]

$$R_T = R_W + (1+k) R_F \quad (7)$$

$$R_F = \frac{1}{2}\rho U^2 S C_F \quad (8)$$

where S, ship hull surface; R_F, the friction resistance; C_F follows the ITTC 1957 formula:

$$C_F = \frac{0.0075}{(\log Re - 2)^2} \quad (9)$$

and the total resistance coefficient (C_T); and wave coefficient (C_W):

$$C_T = \frac{R_T}{0.5\rho U^2 S} \quad (10)$$

$$C_W = \frac{R_W}{0.5\rho U^2 S} \quad (11)$$

The interference resistance of Multihull can be calculated by

$$\Delta R_T = R_{T_{penta}} - (R_{T_{main}} + 4R_{T_{side}}) \tag{12}$$

4. Results and Discussion

Comparative analysis on Multihull between experimental and computation based on Michell's theory has been exposed by Tuck [4], where the shape of the model and configuration had a significant impact on the hydrodynamic performance of Multihull. This analytical research had also been performed based on Michell's theory with the computational tool "Michlet". The analysis results of the various configurations of Wigley and the warp-chine are shown in Figures 3 to 6.

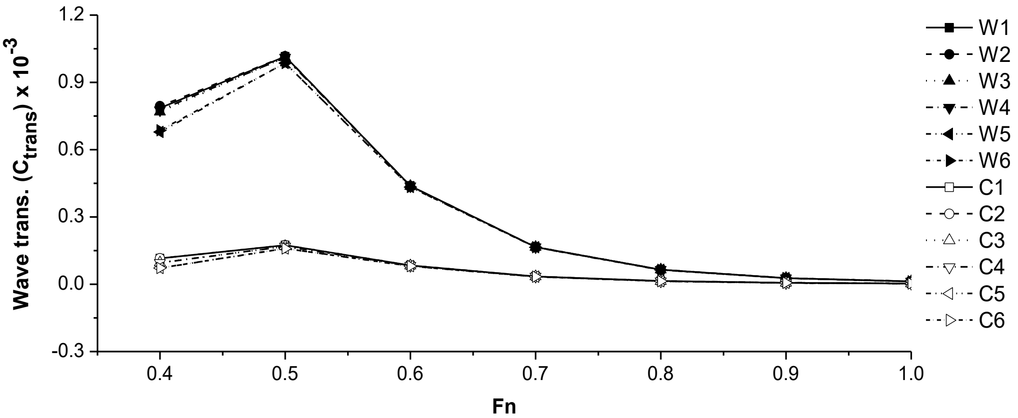

Fig. 3. Comparison of transverse wave coefficients for all configurations of Wigley and warp-chine

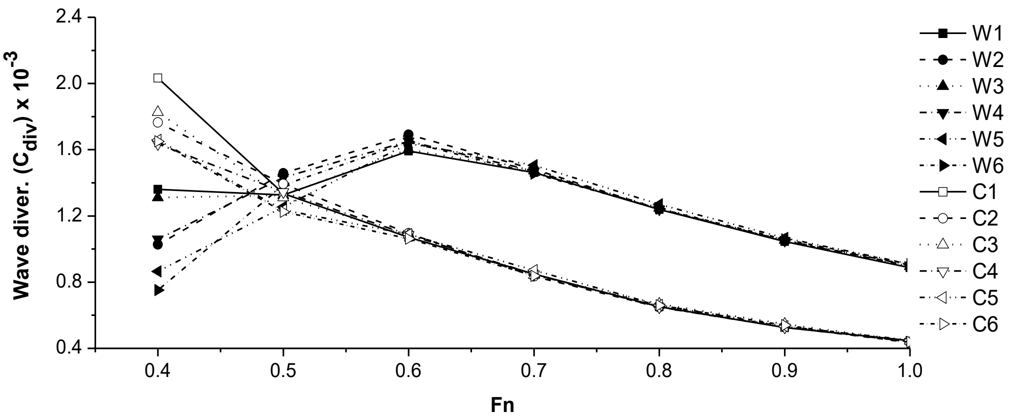

Fig. 4. Comparison of diverging wave coefficients for all configurations of Wigley and warp-chine

The computational results of transverse wave coefficients in Figure 3 is showing the consistent trend for all configurations of warp-chine and Wigley. The warp-chine models are getting a higher reduction than Wigley models with the most substantial deviation at Fn 0.5, on average by 82.8%. The diverging wave coefficients (Figure 4) and the wave resistance coefficient (Figure 5) are showing a similar trend. The warp-chine models have a continuing declining trend, while Wigley models have a hump at Fn 0.6 (Figure 4), and others at Fn 0.5 (Figure 5), then subsequently decreased. The deviation in average between two models for both diverging and wave coefficients are at 24.13% and 36.7%, with warp-chine models still consistent with the lower values. The interference wave (Figure

6), negative interference value is tending to occur at warp-chine models at Fn <0.5. But on increasing Fn, the interference of both models Wigley and warp chine had up and then tended to fall at Fn> 0.6. The deviation in an average of interference coefficient between the two models has reached 58.3%.

The high deviation of the wave resistance coefficient between the warp-chine and Wigley is possible the influence of significant interference factors. Those as a mutually constructive wave of the encounter waves that are generated by each hull. The minimum wave resistance for Wigley configurations is generally formed by an arrangement that the front-side hull and the after-side hull in a line, i.e., W1, W3 and W5. While warp-chine configurations, the lower wave is generally formed by forming as arrow tri-hull, i.e., C2, C4 and C6.

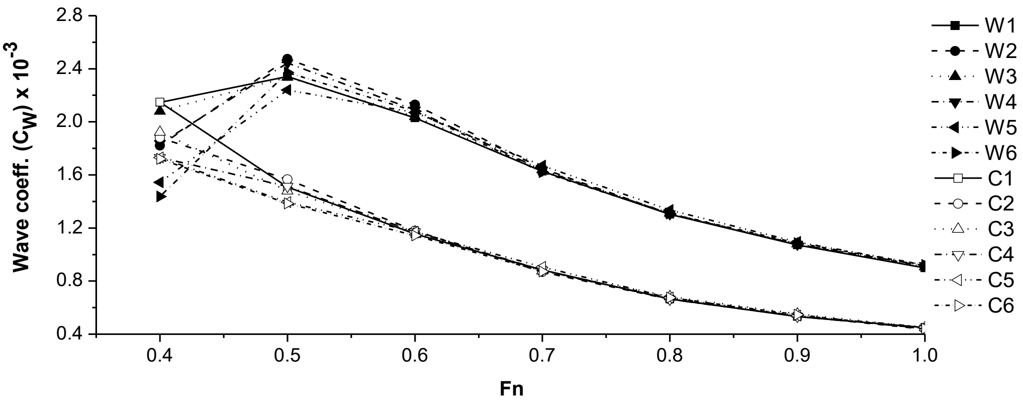

Fig. 5. Comparison of C_W for all configurations of Wigley and warp-chine

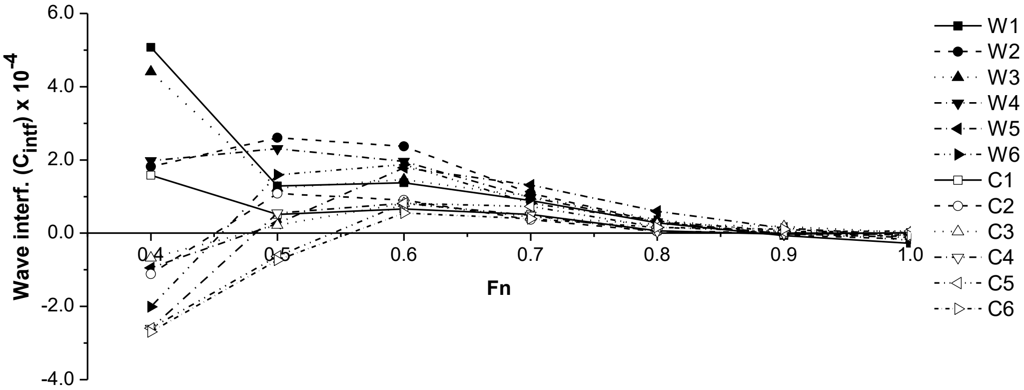

Fig. 6. Comparison of C_{interf} for all configurations of Wigley and warp-chine

The wave resistance from experimental can be calculated by Eq. (7), that is by subtracting the total resistance of the test with the form factor and friction resistance. Further, the wave resistance coefficient can be calculated by Eq. (11). The comparisons of results obtained from calculations by “Michlet” and experiments are not satisfactory, especially at below Fn 0.6, as shown in Figure 7 and 8. The addition of a sign (") on both symbols of Wigley (W) and warp-chine (C) as experimental models. The deviation in average between test and calculation of the wave resistance for Wigley by 8.25% and warp-chine by 11.8%. The difference of calculations and experimental, especially at low speed probable the viscous factors still influential where the theoretical incapable of predicting the valuable.

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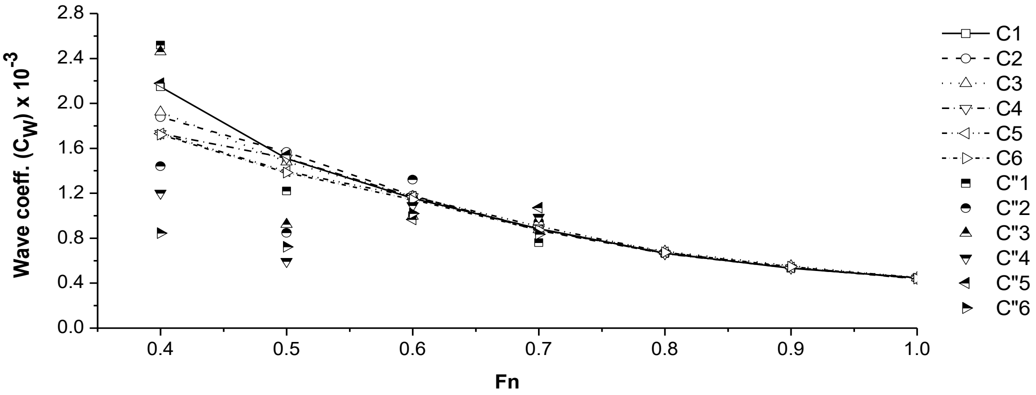

Fig. 7. Wave coefficient comparison for warp-chine models between test and Michlet

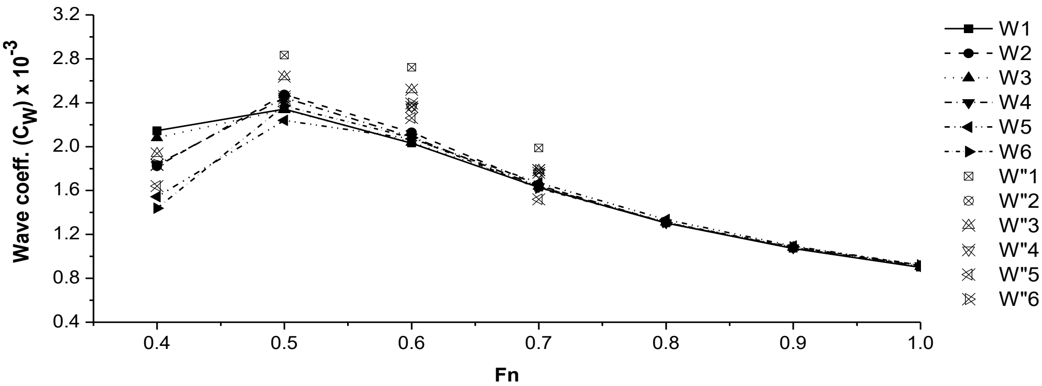

Fig. 8. Wave coefficient comparison for Wigley models between test and Michlet

Yeung *et al.,* [13] stated Multihull generated cross-flow effects representative of the total resistance that can be expressed with the interference of the wave systems in the far-field. The illustration of far-field free-wave patterns on the sectoral patch of the aft of ship by design tool based on Michel integral "Michlet" of warp-chine (a) and Wigley (b) at high speed, Fn 1.0, are shown in Figure 9. The wave pattern characteristics of warp-chine had previously been thoroughly discussed by Sulistyawati, W. [10, 11]. The colour indicates the value of the free-surface wave pattern z = □(x,y) where the deepest troughs with dark blue and the highest crests with nearly white. Comparison wave pattern between two models shows Wigley model more produced massive waves than warp-chine, which is characterised by a more comprehensive white indication. That result is appropriate with the results of experiments and Michlet's calculations that Wigley model produces higher wave resistance than warp-chine (see Figure 5).

5. Conclusion

The experimental and computation based on Michell approximation on pentamaran using Wigley and warp-chine had been performed. All of the wave resistance results showed Michell's theory agreement with the experiments, especially at Fn greater than 0.5 that possible viscous factors were still influential at low speed where the theoretical prediction could not potentially valuable. The greatest deviation of the wave resistance coefficient between the warp-chine and Wigley was possible the influence of large interference factor due to the impact of shape and their configuration. The results of configurations of warp-chine much better than Wigley, except for the diverging resistance at Fn 0.4. High reduction of the warp-chine model was generated from a configuration where the main hull to side hull on formation as arrow tri-hull. While for Wigley model, the high reduction was generated by the configuration that the front-side hull and the after-side hull in a line. Further research is enabling simulation technology to optimise the confinement configuration by applying multi-variation hulls that have been done by other researchers.

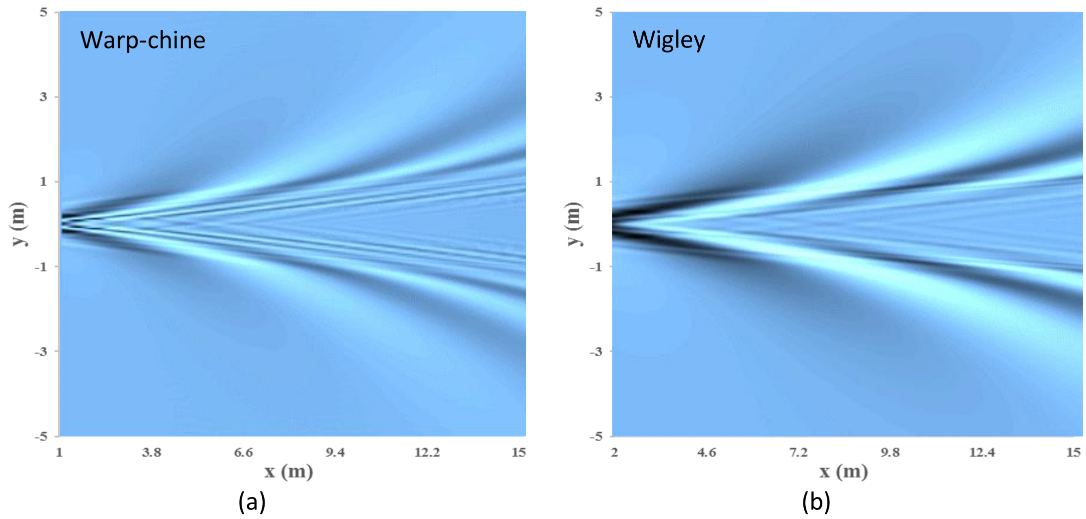

Fig. 9. Far-field wave pattern characteristic of (a) warp-chine and (b) Wigley at Fn 1.0

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