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Research Article

Analysis of Geometries' Effects on Rotating Stall in Vaneless Diffuser with Wavelet Neural Networks

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Wavelet neural network (WNN), which combines the capability of neural network in learning from process and that of wavelet decomposition, was used to study geometry factors on rotating stall in vaneless diffusers. A new error function called cross entropy squared (CSE) function was derived and put forward for the purpose of convergence acceleration. WNN was trained and validated with experimental data from literature. Comparison results showed the reliability. With the trained WNN, detailed investigation was carried out mainly to understand the effects of impeller blade number, blade-exit angle, impeller rotating speed, diffuser radius ratio, and width ratio on stall inception and cell speed of vaneless diffuser. Network results clearly show the existence of distinct stall mechanisms for narrow and wide diffusers, which also make different responses to variation of the above- mentioned parameters.

1. INTRODUCTION

In case of centrifugal compressor widely used in small gas turbines or chemical and petroleum industry, the operating line is chosen at certain distance away from the surge line taking safety into consideration. It is well known that surge of system is always related to stall of either the impeller or the diffuser [1]. Flow separation at large positive incidence angle is regarded as the reason for stall in impeller and vaned diffuser [2]. This paper mainly focuses on vaneless diffuser rotating stall because of the following two reasons: first, diffuser rotating stall is the most common rotating stall type in compressors. Vaneless diffusers are used more often than vaned ones because they have a relatively wider operating range. Second, a vaneless diffuser has simple geometry, and is more preferable for research looking from an experimental as well as theoretical point of view. Therefore, many studies were carried out with both theoretical and experimental methods on rotating stall in vaneless diffusers during the past decades. Theoretical analyses include Jansen [3, 4], Senoo et al. [5, 6], Frigne and Van den Braembussche [7], Tsujimoto et al. [8], Dou and Mizuki [9], and Ljevar et al. [10]. Experimental measurements have been performed by Abdelhamid et al. [11], Abdelhamid and Bertrand [12], Abdelhamid [13], Abidogun [14], Frigne and Van den Braembussche [15], Van den Braembussche and Frigne [16], Shin et al. [17], Nishida and Kobayshi [18], Kobayshi and Nishida[19], Kammer and Rautenberg [20], Ferrara et al. [21], Cellai et al. [22], Kinoshita and Senoo [23], Dou [24], Tsurusaki et al. [25], and Ji et al. [26].

Most of these studies agree on the following conclusions.

(a) Rotating stall occurs when the absolute flow angle reaches a critical value α_{cr}.
(b) This angle strongly depends on diffuser geometry and aerodynamic parameters.
(c) Stall cells rotate in the diffuser at a fraction of the impeller rotational speed.
(d) Number of stall cells present is also influenced by diffuser geometric parameters as well as flow parameters.
(e) Generated instabilities can be measured over the whole axial width of the diffuser.

In spite of all these studies, there is still no consensus on how to predict α_{cr}, how diffuser geometry and flow parameters influence stall characteristics, how stall is initiated, and what the stall mechanisms are. The following is the survey of available literature about stall mechanisms and factors influencing critical angle.

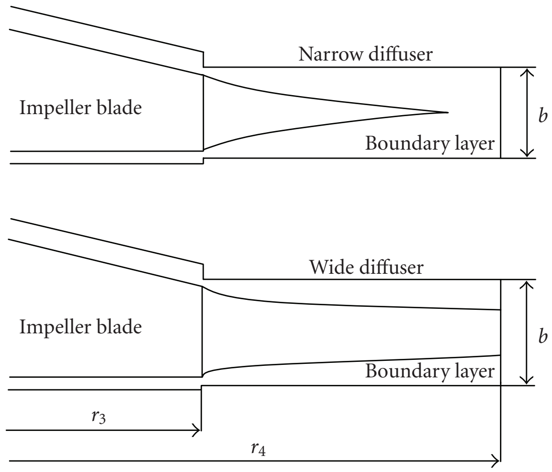


Figure 1: Flow in narrow diffuser and wide diffuser.

1.1. Stall mechanisms

In open literature, there are mainly two kinds of analytical models for rotating stall in vaneless diffusers. One is the way using momentum integral equation of boundary layer (Jansen [3], Senoo et al. [5]). This model links the occurrence of rotating stall to the existence of radially inward flow within boundary layers. But some investigators reported the operating compressors with some reversed flow without flow instabilities or with no reversed flow but with rotating stall [1, 11]. The other model is to study the instability of inviscid core flow or interaction of the core with boundary [7, 8]. Dou and Mizuki [9] and Abdelhamid and Bertrand [12] seemed to combine the above two views and concluded that stall mechanisms were different for narrow diffuser and wide diffuser.

In Figure 1, the vaneless diffuser flow is schematically represented for narrow and wide vaneless diffuser types. Wide diffusers are assumed to have two-dimensional core flow, which separates the wall boundary layers from each other, and narrow diffusers are assumed to have merging boundary layers. This figure vividly depicts why there are two possible mechanisms existed for rotating stall in vaneless diffuser. Unfortunately, those researchers did not make a clear definition about what is wide diffuser, and what is narrow diffuser.

1.2. Factors influencing critical angle

As aforementioned, stall occurs when diffuser inlet absolute flow angle reaches critical angle. So how to predict stall critical angle correctly and precisely is very crucial during design process. Jansen's studies showed that critical angle is a function of diffuser geometry (width ratio and radius ratio) and the fluid Reynolds number. To help the designers to avoid rotating stall, Jansen developed a series of correlations which showed that decreasing width ratio and radius ratio would be beneficial. To correct Jansen's improper assumption of flow in diffuser, Y. Senoo published several papers and established his famous criteria which are accepted widely by the compressor industry. He also identified other parameters that influenced critical angle. These parameters included: Mach number, Reynolds number, radius ratio, width ratio, and most notably the inlet velocity distortion as it suggested that the more disturbed diffuser inlet flow, the greater possibility that diffuser may stall. Y. Senoo criteria indicate that critical angle is hardly affected by Reynolds number in case of narrow diffuser. Van den Braembussche and Frigne [16] showed that Y. Senoo's prediction of the critical diffuser inlet flow angle agreed well with experimental data if a Reynolds number correction was applied. Tsujimoto et al. [8] investigated impeller blade angle's influence on instability of vaneless diffuser and pointed out that upstream impeller had no influence on rotating stall in diffuser. But the analysis carried out by Ljevar et al. [10] showed strong influence of impeller on diffuser stall. Tsurusaki et al. [25] studied rotational speeds of stall cells in vaneless diffusers and critical inlet flow angles for rotating stalls under the condition of no volute experimentally. They also correlated their experimental data and put forward a simple equation for the prediction of critical angle. Works of Nishida and Kobayshi [18, 19] found that discrepancy between their measured and predicted critical angles should be attributed to the discontinuous change between impeller outlet width and diffuser inlet width and the general shape of inlet pinch. Even though, formula of Nishida and Kobayashi also exhibited a large discrepancy when being applied to last stage configuration of a multistage compressor as shown by Ferrara et al. [22, 23]. Ferrara concluded that Nishida and Kobayashi correlation gave reasonable prediction only when $b_2/r_2 > 0.1$. Ferrara's studies showed that diffuser inlet pinch shape had negligible influence on performance and stall incipient angle.

Despite all of the above-mentioned published literature and ongoing researches, there remains no definitive set of criteria for rotating stall avoidance in vaneless diffuser. Disagreements and contradictions still exist towards how many factors and which factors should be taken into consideration towards the prediction of critical angle. Present paper tends to answer the following questions.

(i) What is the parameter that triggers one or other mechanisms of rotating stall?
(ii) How to make a good and simple correlation by using experimental data in literature?
(iv) Are there any differences between the influences of diffuser geometries on stall critical angle of narrow and wide diffusers?

2. METHODOLOGY

In order to show the reason for which neural network method was used, experimental data collected in [16] and new data added by Kinoshita and Senoo in [23] are reproduced here in Figure 2.

It is easy to see that these experimental data are scattered considerably and no trend is apparent.

Besides the scattered data aforementioned, obscure mechanisms for the inception of vaneless diffuser rotating and experimental analyses for all the factors that may

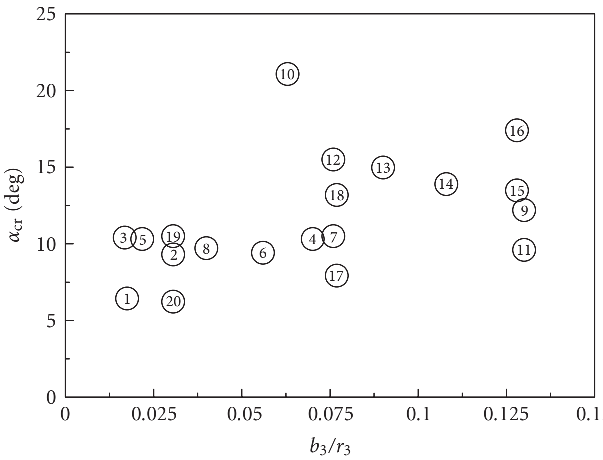


FIGURE 2: Critical inlet flow angle for rotating stall in the literature [16, 23].

influence diffuser stall would be too expensive to be afforded by one lab in terms of cost and test facilities.

Based on the above discussions, a good solution for solving this problem is the implementation of black box model.

(i) It does not use a priori knowledge of the physics under investigation, because of their self-adapting nature. But parameters of the model should be based on measured data.

(ii) It usually has high-mapping capabilities and guarantees a good generalization even with a reduced set of identification data.

Among the various black box models, neural network (NN) has proven to be flexible and robust in simulation. Neural networks have been established as a general approximation tool for fitting nonlinear models from input/output data. Universal approximation property for neural networks has been proved. Widely used neural networks are back-propagation (BP) network and radial basis function (RBF) network. But they all have shortcomings, BP has slow-convergent rate and often gets stuck into local minimum; RBF does not have the problem of local minimum, but specification of hidden layer nodes of RBF is very complicated.

In 1992, Zhang and Benveniste [27] proposed a new notation of wavelet neural network (WNN) as an alternative to feed forward NN for approximating arbitrary nonlinear functions based on wavelet transform theory. Adoption of wavelet basis as squashing function has the following advantages: firstly, the wavelet basis function can be orthogonal which ensures uniqueness of expression of approximation; secondly, the wavelet function is able to adapt to different approximation by changing its scale and translation factors; and finally, wavelet has the characteristic of stepwise refinement, which makes even a better approximation, especially for function with sudden change.

So present authors tried to use WNN to construct mathematical model for critical angle prediction and analyze factors that influence vaneless diffuser stall characteristics. Comparisons with literature results showed the good approximation and identification ability of vaneless diffuser. The paper is organized as follows. In Section 1, literature surveys about vaneless diffuser rotating stall investigations are discussed; methodology and reason for the adoption of WNN are presented in Section 2. Some background knowledge of wavelet analysis, topological structure of WNN, and learning algorithm is given in Section 3; WNN data training and results are reported in Section 4. Finally, factors that influence diffuser rotating stall are analyzed using the trained networks, and conclusions are drawn in Section 5.

3. LEARNING ALGORITHM AND TOPOLOGICAL STRUCTURE OF WNN

Since the results of WNN strongly depend on analyzing wavelet type and structure of the network, it is necessary to give some brief introduction about wavelet analysis and describe exactly the wavelet and the learning algorithm normalization in order to show the substance of these results and to make them repeatable by other investigators.

3.1. *Background of wavelet analysis*

Wavelet analysis is considered as a breakthrough in Fourier analysis. Wavelet has good localization characteristics in both time and frequency domains. Wavelet analysis allows the use of long time intervals where we want more precise low-frequency information, and shorter regions where we want high-frequency information.

Suppose that $\Psi(x)$ is a mother wavelet function, then a group of wavelet bases could be generated through translation and scaling as follows:

$$\Psi_{a,b}(x) = \frac{1}{\sqrt{a}}\Psi\left(\frac{x-b}{a}\right), \tag{1}$$

where a is the scaling factor, b is the translation factor, and $\Psi_{a,b}(x)$ is the wavelet function. $\Psi(x)$ should satisfy a frame condition which was detailedly discussed in Daubechies [28].

3.2. *Topological structure of wavelet neural networks*

Structure of WNN is similar to RBF network except that the radial functions are replaced by orthonormal bases (i.e., scaling functions in the theory of wavelet analysis).

Figure 3 depicted the basic structure of multi-input and multioutput WNNs. The model could be expressed as follows:

$$y_j = S\left[\sum_{i=0}^{n} W_{ij}\Psi_{a_i,b_i}\left(\sum_{k=0}^{m} W_{ki}x_k\right)\right], \tag{2}$$

where $S(\cdot)$ is a sigmoid function.

3.3. *Learning algorithm*

Error back-propagation algorithm of gradient type was applied in the present WNN to adjust wavelet coefficients and network weights.

Suppose that x_p^k is the pth input pattern, y_i^p is the pth pattern's actual output, and d_i^p is the target output.

In order to improve convergence, many investigations have been carried out on error function. Traditional BP network uses mean-squared-error function (MSE). However, MSE surface is a multidimensional super surface which influences convergence rate and easily causes convergence process to be trapped to local minimal value. Karayiannis and Venetsanopoulos [29] put forward a cross-entropy (CE) error function to accelerate convergence and overcome premature saturation during training process. The concept of entropy is similar to Shanon's definition. CE can be written as follows:

$$E = \sum_{p=1}^{P}\sum_{j=1}^{N}\left[d_i^p \ln y_i^p + (1-d_i^p)\ln\left(1-\ln y_i^p\right)\right]. \quad (3)$$

However, this function suffers from over specification for training patterns since the error signal for a correct saturated output node is too strong. Also the minimum of (3) is not zero. Present authors made further modification to the CE, and the resulted function was called cross-entropy squared error (CSE) function whose accelerate rate was of second-order and minimum value was zero,

$$E = \frac{1}{2}\left\{\sum_{p=1}^{P}\sum_{j=1}^{N}\left[d_i^p \ln \frac{y_i^p}{d_i^p} + (1-d_i^p)\ln\frac{\left(1-\ln y_i^p\right)}{1-d_i^p}\right]\right\}^2. \quad (4)$$

The weights and wavelet factors are updated to minimize the error-function E according to gradient-descent algorithm with learning rate α and momentum factor η as follows:

$$\begin{aligned}
W_{jk}(k+1) &= W_{jk}(k+1) - \eta\frac{\partial E}{\partial W_{jk}} + \alpha\Delta W_{jk}(k),\\
W_{ki}(k+1) &= W_{ki}(k+1) - \eta\frac{\partial E}{\partial W_{ki}} + \alpha\Delta W_{ki}(k),\\
a_i(k+1) &= a_i(k+1) - \eta\frac{\partial E}{\partial a_i} + \alpha\Delta a_i(k),\\
b_i(k+1) &= b_i(k+1) - \eta\frac{\partial E}{\partial b_i} + \alpha\Delta b_i(k).
\end{aligned} \quad (5)$$

Taking simple form into consideration, Morlet wavelet was chosen as a transform basis function for hidden layer:

$$\Psi_{a_i,b_i}(x) = \cos\left(1.75x_z\right)e^{-x_z^2/2}, \quad (6)$$

where $x_z = (x-b_i)/a_i$.

As the wavelet basis function was very sensitive to scaling and translation coefficients, the initial values should be chosen carefully. Further, the number of wavelet basis nodes should be large enough to ensure the stability. Initial values of network parameters were given in Table 1.

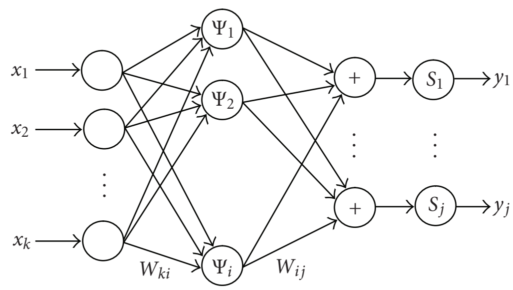


FIGURE 3: Sketch of the structure of WNN.

TABLE 1: Initial values of WNN.

Parameters	Initial values
W_{ki}	Random between −0.5 and 0.5
W_{ij}	Random between −0.5 and 0.5
a_i	Random between −0.5 and 0.5
b_i	Random between −1.0 and1.0

4. MODELING OF CRITICAL ANGLE FOR DIFFUSER ROTATING STALL

4.1. Selection of input nodes and output nodes

Even factors that may influence diffuser rotating stall include Mach number, Reynolds number, diffuser width ratio, diffuser radius ratio, impeller blade number, impeller exit angle, discontinuous change between impeller outlet, diffuser inlet, diffuser inlet shapes, inlet velocity distortion, and influences of downstream components. We had to overlook some of these factors for the following reasons.

(i) Most of the available experimental researches having detailed geometry data and stall characteristics were done on low-speed facilities. Mach number of impeller tip speed was lower than 0.5. And according to Senoo and Kinoshita [6], Mach number at or below this level had negligible influence on critical angle. So Mach number was removed from consideration.

(ii) Diffuser inlet shape could not be expressed quantitatively, so it was also removed.

(iii) Even if inlet distortion has nonnegligible influences on inception of rotating stall, we still have to remove it. As the published data did not always contain all necessary conditions and it was difficult to measure inlet flow distortion.

For stall characteristics, cell number, critical angle, and cell speed were the most three important parameters. As the cell number and cell speed strongly depended on flow condition, so here we defined them as the values at the incipience of stall.

At first, the author tended to use specific speed as one of the input parameters since it may be a much more relevant and meaningful variable. However, not all required parameters were available in cited references. And most geometric parameters had been included, so the authors thought that it was enough.

Till now, we could define N_b, β_{2A}, ω_i, r_4/r_3, b_3/r_3, b_3/b_2 as nodes of input layer and $\alpha_{\rm cr}$, $\Omega_{\rm rs}$ as nodes of output layer.

4.2. Data collection

For a successful application of WNN, it is necessary to collect as many training data as possible. Besides data volume, quality and representation are also important. A good training set should contain routine, unusual, and boundary condition. Data collection and process followed the next several principles.

(i) Only experimental results were selected for training, and theoretical results were used for analysis reference.
(ii) Flow coefficient and cell speed were reprocessed into nondimensional form.
(iii) Collected data were arranged into two sets: one for training and the other for validation. It was important to note that the error criterion function used for training only accounted for modeling error which entailed that the obtained model is depending on the training set. This introduced the next principle.
(iv) Data should be representative and cover as large range as possible for each parameter.

For the gathered samples, range of N_b was from 5 to 28; β_{2A} varied between 0.0° and 65.4°. Coverage of diffuser width was especially wide taking account of disagreements towards possible existing different stall mechanisms.

4.3. Data processing

Data processing was also an important consideration. Some of the data need to be converted into another form to be meaningful to the WNN. Further, the data should also be normalized in order to make the transform function operating properly. The normalization was performed with respect to the maximum and minimum values of the training set for each input and output unit so that the normalized values lay in the range [0, 1].

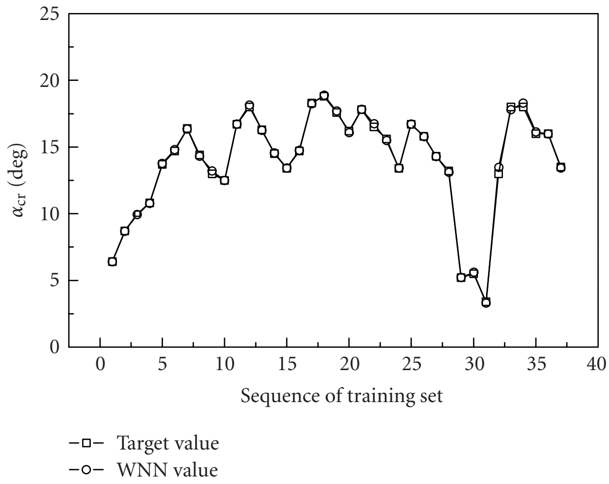
4.4. Training results and validation

Except the data in Table 2, there are totally 37 groups of data for training collected from [2, 11–17, 20] and some personal communications. One more thing that should be mentioned here is that test facilities of almost all the available literature, related to rotating stall in vaneless diffuser, were compressors with relatively low rotating speed and pressure ratio. Though WNN had some certain ability of extrapolation, it was still reasonable not to predict the results using parameters out of the training range. From this point of view, the resulted WNN may only be applicable for compressors with rotation speed lower than 5000 rpm which was the largest value in training set.

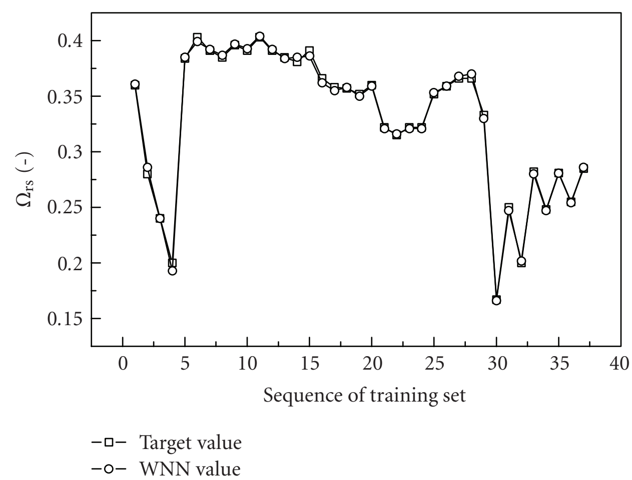
After 8000 times of iteration, the residual decreased to predefined convergence standard. In order to make comparisons, output results of WNN were recalculated due to normalization of input data. At a glance, comparisons for the training set of WNN between target values (i.e., experimental values) and WNN values (i.e., numerical values) were given in Figures 4(a) and 4(b).

It could be observed that the proposed WNN produced the test samples with great accuracy. Maximum relative error was 3.69% for critical angle and 2.14% for cell speed.

Derived WNN was further tested against measured data from [12] (N_b: 8; ω_i: 523.1 rad/s; β_{2A}: 27°). Results were listed



(a) Comparison for absolute critical flow angle



(b) Comparison for dimensionless cell speed

FIGURE 4: Training results.

in Table 2. In that table, hyphen meant that α_{cr} was unavailable in literature. From Table 2, it could be calculated that maximum relative error for cell speed was 8.2%. As the experimental data were scarce in literature, so the authors had to keep most of the data for training and these data were without critical angle for validation. But resulted trends of critical angle were the same as those given in conclusion [12].

In conclusion, the agreement of WNN values with measured ones was generally acceptable.

5. ANALYSIS OF GEOMETRY FACTORS ON STALL INCEPTION

In order to analyze effects of geometries on diffuser stall, two representatives coming from training set were chosen. One was from [23] with very low-width ratio standing for narrow diffuser, and the other from [2] representing wide diffuser. In the following subsections, discussions are all based on these two data. Without notification, points with mark "*" are experimental data. All the other data are test data

Table 2: WNN validation.

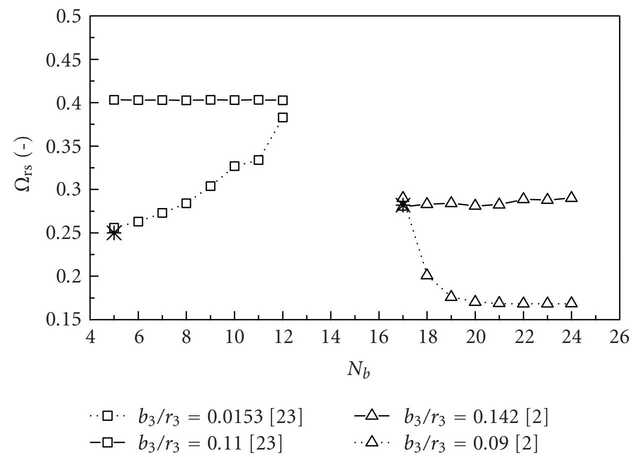
Configuration	Output variable	Measured value	WNN value
$r_4/r_3 = 1.55$, $b_3/r_3 = 0.076$ Cell number = 2	Ω_{rs}	0.3541	0.383
	α_{cr}	—	14.6°
$r_4/r_3 = 1.55$, $b_3/r_3 = 0.09$ Cell number = 1	Ω_{rs}	0.3361	0.3610
	α_{cr}	—	11.5°
$r_4/r_3 = 1.55$, $b_3/r_3 = 0.108$ Cell number = 1	Ω_{rs}	0.3241	0.3429
	α_{cr}	—	11.5°
$r_4/r_3 = 1.55$, $b_3/r_3 = 0.126$ Cell number = 1	Ω_{rs}	0.3121	0.2902
	α_{cr}	—	8.43°
$r_4/r_3 = 1.83$, $b_3/r_3 = 0.076$ Cell number = 2	Ω_{rs}	0.2701	0.2872
	α_{cr}	—	19.6°
$r_3/r_2 = 1.83$, $b_3/r_3 = 0.108$ Cell number = 1	Ω_{rs}	0.2641	0.2715
	α_{cr}	—	17.7°
$r_4/r_3 = 1.55$, $b_3/r_3 = 0.126$ Cell number = 1	Ω_{rs}	0.2641	0.2550
	α_{cr}	—	14.5°
$r_4/r_3 = 1.73$, $b_3/r_3 = 0.126$ Cell number = 2	Ω_{rs}	0.2461	0.2398
	α_{cr}	—	13.4°

given by WNN in the following graphs. The estimated uncertainty in the critical flow angle and cell speed was ±4% and ±5%.

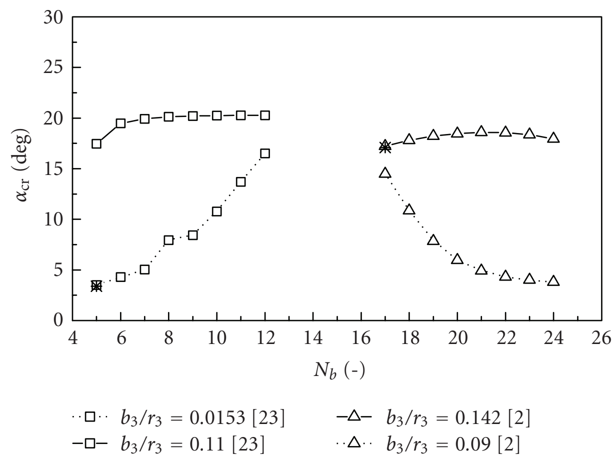
5.1. *Effects of blade number*

There were few papers which concerned blade number's effect on stall inception except for Ljevar et al. [10] in which two-dimensional model was used. Currently, blade numbers of two chosen samples were increased gradually and their effects on critical angle and cell speed were shown in Figures 3(a), 3(b). $b_3/r_3 = 0.0153$ and $b_3/r_3 = 0.142$ were the experimental diffusers' width ratios of [2, 23], respectively. It could be observed that diffuser with different width ratio exhibited distinct responses to the increment of blade number. In order to find out at which width ratio, blade number's influence might change which implied that different flow mechanisms might be existed. Width ratio of diffuser in [23] was increased gradually from 0.0153 to 0.11, and that of diffuser in [2] was decreased from 0.142 to 0.09. For each of these width ratios, blade number was varied. During these predictions, other nonmentioned parameters were kept as constants. Blade number's influence did not change abruptly until the width ratio of [23] was increased to be larger than or equal to 0.11, and the other was decreased to be equal in or smaller than 0.09.

The influence on the critical angle indicated that proper choice of blade number can contribute to better stability of vaneless diffuser.



(a) Effects of blade numbers on cell speed

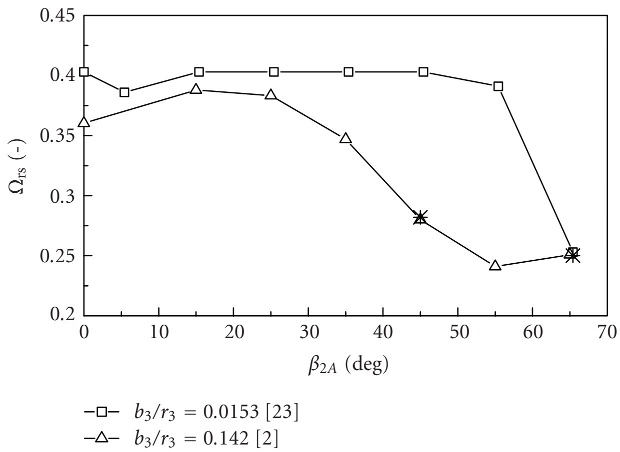


(b) Effects of blade numbers on critical angle

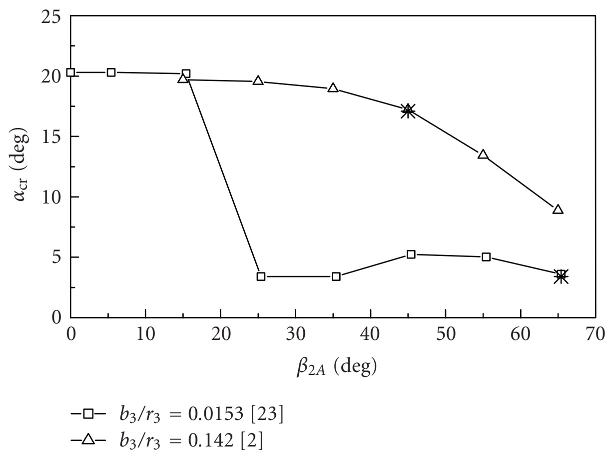
Figure 5

5.2. *Effects of blade-exit angle*

Figures 6(a) and 6(b) showed the variation of cell speed and critical angle with blade-exit angle.

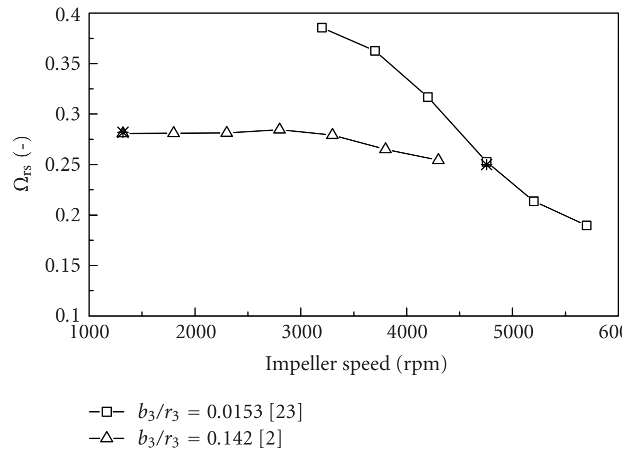


(a) Effects of blade-exit angle on cell speed

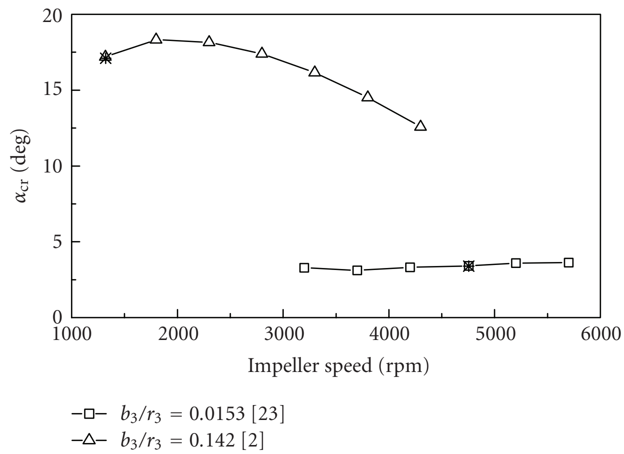


(b) Effects of blade-exit angle on critical angle

FIGURE 6



(a) Effects of impeller rotational speed on cell speed



(b) Effects of impeller rotational speed on critical angle

FIGURE 7

It could be observed that increasing blade-exit angle tends to increase diffuser stability and decrease cell speed. Increasing blade-exit angle tends to make the slope of impeller performance curve negative. Even under such negative slope curve of diffuser, diffuser could be still stable.

5.3. *Effects of impeller rotational speed*

Keeping other parameters unchanged, effects of impeller speed on cell speed and critical angle were presented in Figures 7(a) and 7(b).

In case of larger values of width ratio, critical angle was reduced by six degrees due to a change of impeller speed, but in the case of small value of width ratio, critical angle was hardly affected by impeller speed. A variation of impeller speed meant changing diffuser inlet Reynoldsnumber which was defined as Re = Ub_3/v, in which U was the main flow velocity. From this point of view, the above conclusions compared well with those of [6].

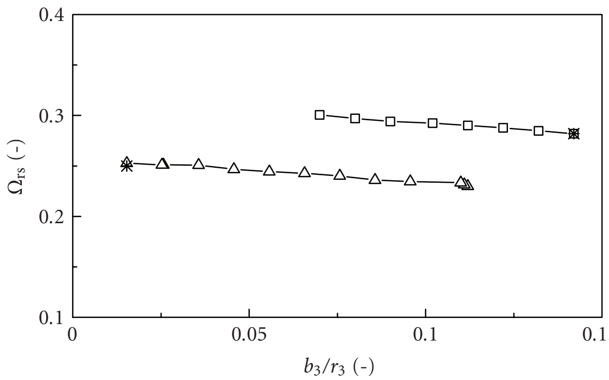
5.4. *Effects of diffuser width ratio*

Figures 8(a) and 8(b) showed the variation of critical flow angle and cell speed at stall onset with diffuser width ratio.

That is, critical angle increased as diffuser width ratio was increased. In other words, decreasing width ratio resulted in an increase in the stability. Even this trend agreed well with Jansen [4], but it contradicted with Abidogun [14] and the data shown in Table 2. So the author would like to claim that whether increasing diffuser width ratio would weaken or enhance system stability also depended on some other factors which may be discussed in the next subsection. At the same time, rotational speeds of cells were found to depend weakly on diffuser width ratio.

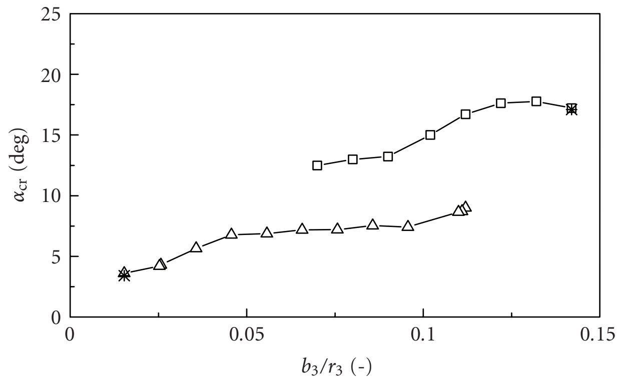
5.5. *Effects of diffuser radius ratio*

For fixed diffuser width ratio, variations of critical angle and cell speed at stall onset with radius ratios were shown in Figures 9(a) and 9(b).



—△— r_3/r_2 = 1.4 [23]
—□— r_3/r_2 = 1.5 [2]

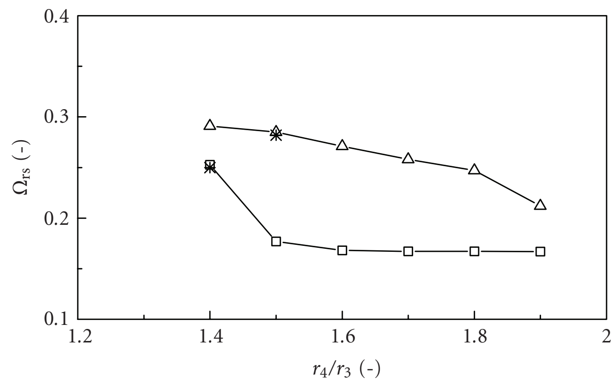
(a) Effects of diffuser width ratio on cell speed



—△— r_3/r_2 = 1.4 [23]
—□— r_3/r_2 = 1.5 [2]

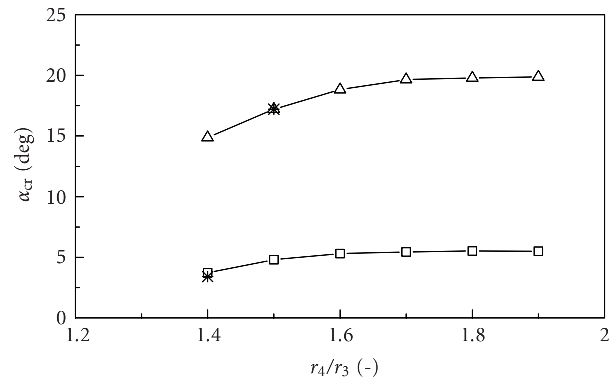
(b) Effects of diffuser width ratio on critical angle

FIGURE 8



—□— b_3/r_3 = 0.0153 [23]
—△— b_3/r_3 = 0.142 [2]

(a) Effects of diffuser radius ratio on cell speed



—□— b_3/r_3 = 0.0153 [23]
—△— b_3/r_3 = 0.142 [2]

(b) Effects of diffuser radius ratio on cell speed

FIGURE 9

Through comparison with Figure 8(a), the rotational speeds were depending strongly on the diffuser radius ratio and weakly on width ratio. The larger the diffuser radius ratio, the smaller the rotational speed of the cell. This could be explained as follows. The stall cell is generally large for long diffuser, so it would need more energy for rotation. Diffuser was a component with no energy feed, so stall cell had lower speed. Change of diffuser radius ratio exhibited different effects for diffuser with large width ratio and the one with small width ratio. For $b_3/r_3 = 0.0153$, critical angle was little influenced by exit/inlet radius ratio. For $b_3/r_3 = 0.142$, the larger the radius ratio, the higher critical flow angle. It meant that increasing diffuser length would destabilize the diffuser flow. The above points totally agreed with Senoo and Kinoshita [6].

The above trends could be explained as follows. For narrow diffuser, reverse flow often occurred near inlet which was responsible for stall, so increasing radius ratio had negligible influences on α_{cr}; for wide diffuser, core flow instability, which often occurred downstream of diffuser, could lead to stall. So if diffuser radius was shorter than the point where core flow instability happened, the diffuser would be stabilized with decreasing of α_{cr}. So for vaneless diffuser with large radius ratio, decrease width towards outlet might be helpful from the point of stability.

6. CONCLUSIONS

WNN was used to study geometry factors on stall inception of vaneless diffuser. The research was carried out in two steps: firstly, measured data from literature were collected, and WNN was trained; secondly, each parameter of input layer was varied while others were kept constant to study the variable's influence on critical angle and cell speed at stall onset. Obtained results could be summarized as follows.

(i) Diffusers with large width ratio and small width ratio response differently for variation of one same parameter. Such differences suggest the possible existence of two mechanisms which could be responsible for the occurrence of instability in impeller and diffuser combinations.

(ii) Change of impeller blade number has little influences on cell speed and critical angle for wide diffuser, whilst it has large influence on narrow diffuser, but no particular trends could be found.
(iii) Increasing blade-exit angle tends to stabilize diffuser flow.
(iv) Increasing impeller speed could reduce critical angle for wide diffuser. But in case of small value of width ratio, critical angle is hardly affected by impeller speed.
(v) Contradicted results are found by WNN about the influence of width ratio on critical angle. Some results show that increasing width ratio has certain stabilizing effects, while others give totally different opinions. It could be explained as follows: width ratio has distinct effects for diffuser with different radius ratio.
(vi) The larger the radius ratio, the smaller the cell speed. For wide diffuser, the larger the radius ratio, the larger the critical angle. But for narrow diffuser, the critical angle is little influenced by radius ratio.
(vii) For current paper, as b_3/b_2 values of training set are generally near unity, and it is unreasonable to make extrapolation, this parameter has negligible influence on critical angle. This agrees with the correction equation given by Nishida and Kobayshi [18, 19]. In that equation, if b_3/b_2 equals one, then the correction term is eliminated.
(viii) WNN seems to reproduce and correlate experimental data with more accuracy than ordinary methods taking linear and polynomial fits as examples.

NOMENCLATURE

x_k: Input vector
a_j, b_j: Scaling factor and translation factor of wavelet in hidden layer
y_j: Output vector
W_{ij}: Connection weight between output unit j and hidden unit i
W_{ki}: Connection weight between input unit k and hidden unit i
P: Sum of input patterns
m, n, N: Sum of input, hidden and output nodes
r_2: Impeller outlet radius
b_2: Impeller outlet width
b_3: Vaneless diffuser inlet width
b_3/r_3: Vaneless diffuser width to inlet radius ratio at parallel section
r_3: Vaneless diffuser inlet radius at parallel section
r_4: Vaneless diffuser outlet radius
r_4/r_3: Vaneless diffuser radius ratio
N_b: Impeller blade number
ω_{rs}: Stall cell speed (rad/s)
ω_i: Impeller speed (rad/s)
$\Omega_{\text{rs}} = \omega_{\text{rs}}/\omega_i$: Dimensionless cell speed
β_{2A}: Blade-exit angle from radial direction (deg.)
α_{cr}: Stall critical angle from tangential direction (deg.)

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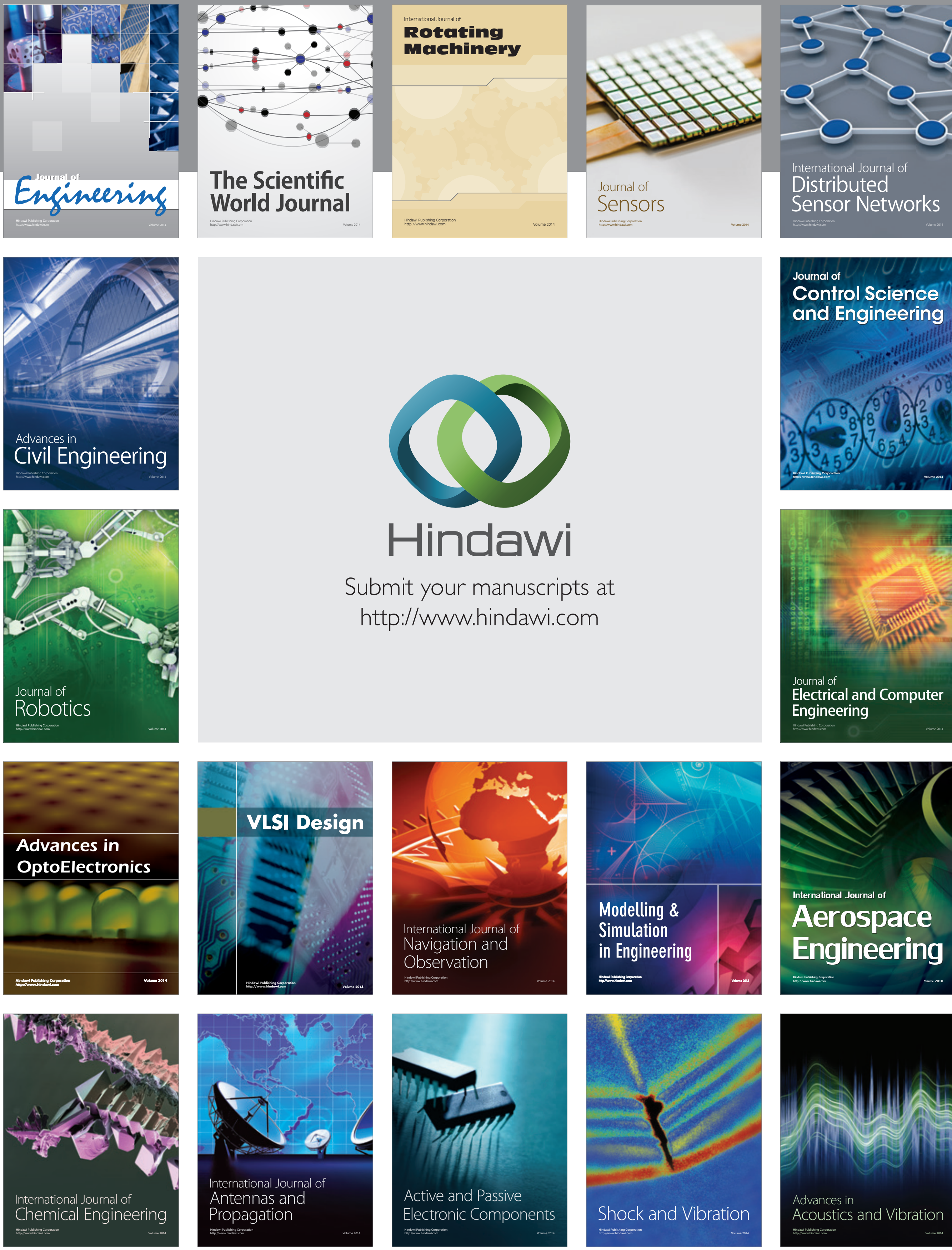
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