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Theoretical Prediction of Fluid Elastic Instability in Finned Tube Array Subjected to Air Crossed Flow

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ABSTRACT: Fluid elastic instability is a major cause of failure of heat exchanger which may result in a relentless accident and commercial loss. The current paper aims to describe the theoretical method for the study of fluid elastic instability in parallel triangular finned tube arrays subjected to air cross flow. Critical velocity at instability was calculated theoretically by using Connor's equation. Connor's equation gives the relationship between the mass damping parameter and reduced velocity. For the theoretical analysis, plain tube and finned tube were considered. Tubes with spiral fines with different fin densities and fin heights were analyzed. Modeling of the tube was done using CATIA software. Natural frequency and logarithmic decrement of the test tube with different fin geometry was calculated by modal analysis and harmonic analysis using ANSYS 19.0. For the analysis, Connors constant is assumed as 4.1. TO compare the results of the finned tube array with plain tube, the effective diameter of the tube was considered. The research outcomes help to understand the effect of pitch ratio, tube array pattern, and fin density on the instability threshold without doing any experimental work. This will also help in the future to compare the results between the theoretical and experimental procedures.

KEYWORDS: Velocity, Harmonic Analysis, Natural Frequency, Logarithmic Decrement**,** Parallel Triangular Tube array.

1. INTRODUCTION

Shell and tube type of heat exchangers with very high shell side cross-flow velocity are most commonly used in the nuclear industry, chemical industry, and process industries. Though heat exchangers with very high cross-flow velocity give maximum efficiency, it results in flow-induced vibrations. There are different mechanisms responsible for flow-induced vibration viz. vortex shedding, acoustic resonance, turbulent buffeting, and fluid elastic instability. Many researchers have studied in detail various mechanisms responsible for flow-induced vibration on the plain tube with different tube array geometry, for different pitch ratios and fluid flows. (Connors, 1980) (Mitra, Dhir, & Catton, 2009) (Mitra et al., 2009) The experimental and numerical investigation has been carried out for different pitch ratios ranges from 1.2 to 1.7for normal triangular, parallel triangular, inline square and rotated square tube array. To identify critical

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flow velocity which is responsible for flow-induced vibration, different types of fluid flows i.e. single-phase flow and two-phase flow consisting of water, air, air-water, water-steam also different refrigerants are used.
From the last two decennia, flow-induced vibration on finned tube arrays has been studied. Compare to a plain tube, finned tube arrays are more entanglement for analysis. In the current paper effect of different finned tube arrays with fin geometry and tube geometry on the critical flow, velocity has been reviewed. Tube material, tube pitch to diameter ratio, fin types, fin thickness, fin pitch, fin height, and fluid type are considered as parameters and their effects on stability threshold are discussed.
In this paper, theoretical calculations of critical velocity at instability were done based on Connor's equation. The finned tube of 19.05mm base diameter with different fin geometry was considered. Input parameters required for theoretical design were calculated using available literature. Natural frequency and logarithmic decrement were calculated by numerical analysis.

II. THEORETICAL DESIGN PARAMETERS

According to (Connors, 1978) in fluid elastic and self-excited vibrations critical velocity of fluid flow can be calculated by equation 1.

$$\frac{Vc}{f_n D_e} = K\left(\frac{m\delta}{\rho D_e^2}\right)^{\frac{1}{2}} \text{ .... (1)}$$

where K is threshold instability constant also known as Connors constant depends on tube pattern and tube spacing. In the above equation, $\frac{Vc}{f_n D_e}$ the reduced velocity factor and $\left(\frac{m\delta}{\rho D_e^2}\right)^{\frac{1}{2}}$ is a mass damping parameter. From the above equation, critical velocity 'Vc' is directly proportional to the natural frequency of tube 'f_n', the mass of tube 'm' and logarithmic decrement of finned tube 'δ'.The effective diameter D_e is the mean diameter of the tube considering the effect of the fin.

Finned Tube Geometry
For the study, plain tube and finned tubes were used. Tubes with spiral fines were considered for the design of the experimental setup. CAD model of a finned tube and plain tube.

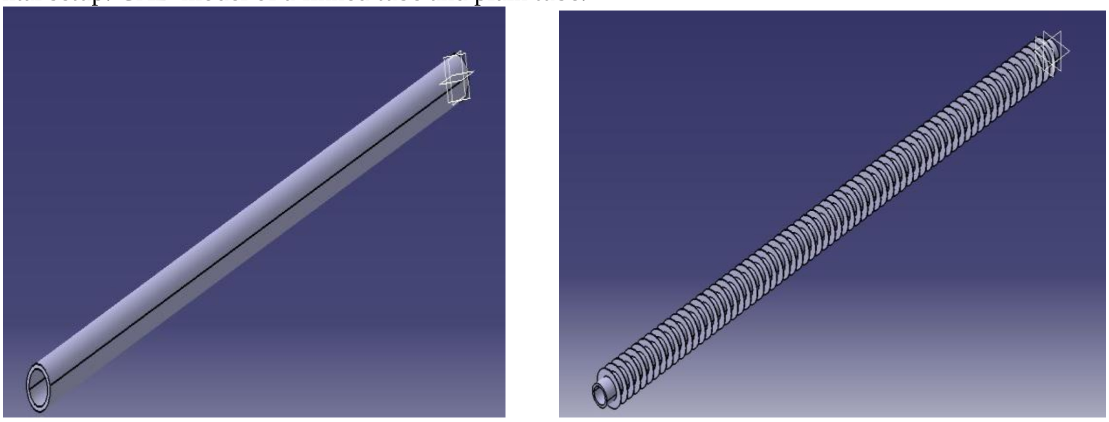

Fig.1. (a)Plain tube Geometry and (b) Spiral Fines Tube With Different Fin Geometry

The main constraint of the design of the flexible tube pattern was to maintain pitch ratio as little as possible so that the experimentation could be done for the design of a heat exchanger which applicable for nuclear reactors. For the current experimental design tube with a 19.05mm base diameter was selected. Array with nine finned tubes with 34mm pitch was considered. Fin pitch for Coarse fins with 8.467mm (3fpi) and fine fins with 2.82mm (9fpi) was considered. Pitch of Here, fin thickness t_p was kept constant as 0.5mm and fin height h_f varied as 3mm and 6mm. Tube preparation consists of a tube with the threaded rod at one end and another end is free. The rod length is the parameters used to tune the tube to the desired natural frequency. Also, the rod will reduce the effective stiffness of the tested tube to better simulate the natural frequencies of the much longer tubes used in service.
From the above input parameters, the initially effective diameter of the fin was calculated. Two different methods exist for the calculation of the effective diameter of the finned tube. The first one is based on the projected front area of fin and tube which is called a volumetric diameter of the tube given by the equation (Hirota, Nakamura, Kikuchi, Isozaki, & Kawahara, 2018)

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$$D_e = \sqrt{(D_f^2 - D_b^2)\frac{t_f}{p_f} + D_b^2} \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

The second method is also based on the volume of fin proposed by (Mair, Jones, & Palmer, 1975) effective diameter of the tube can be given by

$$D_e = \frac{1}{p_f}[t_f(D_f - D_b) + p_f D_b] \ldots\ldots\ldots\ldots\ldots\ldots(3)$$

where D_f finned tube diameter, D_b outer diameter of the tube, t_f fin thickness and p_f fin pitch intensity. Here both methodologies used are based on plain fins with no serrations or twists. Furthermore, the use of these "effective diameters" essentially assumes that the effects of fins can be putative simply by augmenting the diameter of a base tube. (Wang & Weaver, 2010) studied fluid elastic instability from finned tube arrays and found good results. The use of Mair et al.'s effective diameter proved to be a useful predictor for vortex shedding from these finned tubes. In the current work, tube Mair et al.'s effective diameter was considered. The detailed selection of geometric parameters are given in Table 1

Table 1: Geometric Parameters of Finned Tubes

Sr. No	Base tube Diameter (D)	Fin Tube Diameter (D_f) mm	Fin thickness (t_f) in mm	Fin Pitch (p_f) in mm	Effective Diameter (D_e) in mm.	Pitch Ratio (P/D_e)
1	19.05	25.05	0.5	8.467	19.41	1.75
2	19.05	25.05	0.5	2.822	20.13	1.69
3	19.05	31.05	0.5	8.467	19.77	1.72
4	19.05	31.05	0.5	2.822	21.17	1.61

Tube Array Specifications

To maintain the required stiffness and natural frequency, testing tubes are connected with a small threaded bolt. The tube array pattern was kept fixed at one end and the other end is free to vibrate for all tubes. The detailed specification of the tube array pattern considered is given in Table 2

Table 2: Tube array specification

Sr. No	Title	Specification	Sr.no	Title	Specification
1	Tube material	Stainless steel	7	Fin thickness, mm	0.5
2	Fin material	Stainless steel	8	No. of tubes	9
3	End condition	Cantilever	9	Fin height, mm	3 and 6
4	Tube O.D, mm	19.05	10	Fin pitch, mm	8.467 and 2.822
5	Tube I.D, mm	15.05	11	Finning length, l, mm	590
6	Fin type	Spiral	12	Tube pitch in mm	34

III. ANALYTICAL RESULTS

Damping and Natural Frequency:

The tube frequency is decided principally by the rod length and tube mass. When the tube mass has been resolved, the rod length will be the only factor arousing that affects the natural frequency of the tube. The deciding factor is that the rod length determines the distance between the base plate and the test section, which then affects other assemblies and the supporting structure. Therefore, the rod length must be anxiously stubborn to set the desired natural frequency range of the tubes. Initially, modal analysis was done to determine the resonant frequency of the tube using Ansys 19.0. Modeling of the tube was done using CATIA software which was further imported in Ansys workbench. Modal analysis is the simplest method used to calculate natural frequency and resonant frequency reason irrespective of the amount of load acting on it. Considering the feasibility and availability of flow rate, tube length was decided so that it would give the desired natural frequency. Once tube specification and natural frequency were finalized, the harmonic analysis was done to calculate logarithmic decrement. Harmonic analysis is determining the steady-state sinusoidal response to sinusoidal varying loads all acting at a specified frequency. Some load types can be applied with a phase offset. A non-zero displacement load can be applied in harmonic analysis. Natural frequencies were noted from the frequency domain plot for plain tube and finned tube. Sample vibration respoce for the plain tube is as shown in fig. 2

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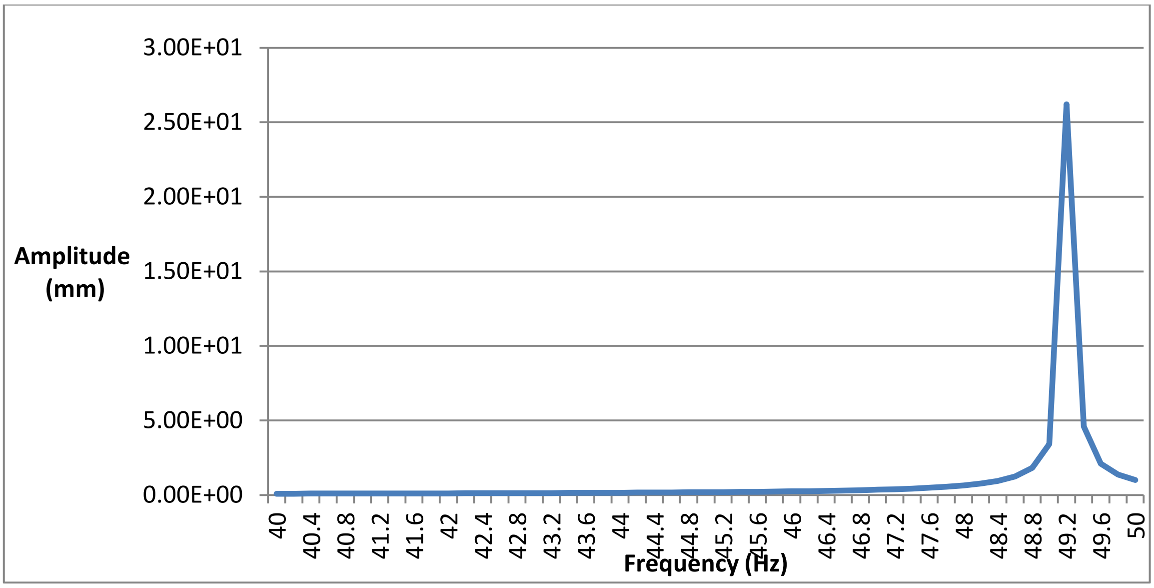

Fig. 2. The natural frequency of Plain Tube

Similarly, vibration response for the finned tube was recorded. Results are tabulated as shown in Table 3. Sample frequency response curve obtained for the finned tube with 6mm fin height and 8.47mm fin pitch is as shown in fig. 3

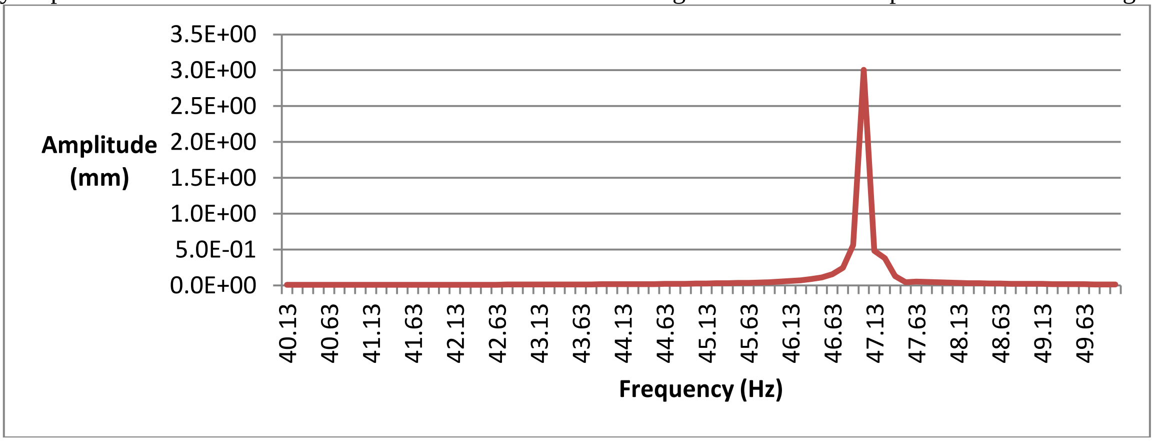

Fig. 3. Amplitude vs. Frequency for Finned Tube (6mm fin height and 8.47mm fin pitch)

Logarithmic decrement is calculated by two methods. The first method is based on the time domain plot where logarithmic decrement can be given by natural log the ratio of the amplitudes of any two successive peaks.

$$\delta = \frac{1}{n}\log\left(\frac{x_1}{x_n}\right). \quad ....(4)$$

The second method is the half bandwidth method, based on the Fourier transform, where the frequency domain plot is used to determine the damping ratio ζ. The damping ratio is calculated by determining the width of the peak of the amplitude as shown in fig.4

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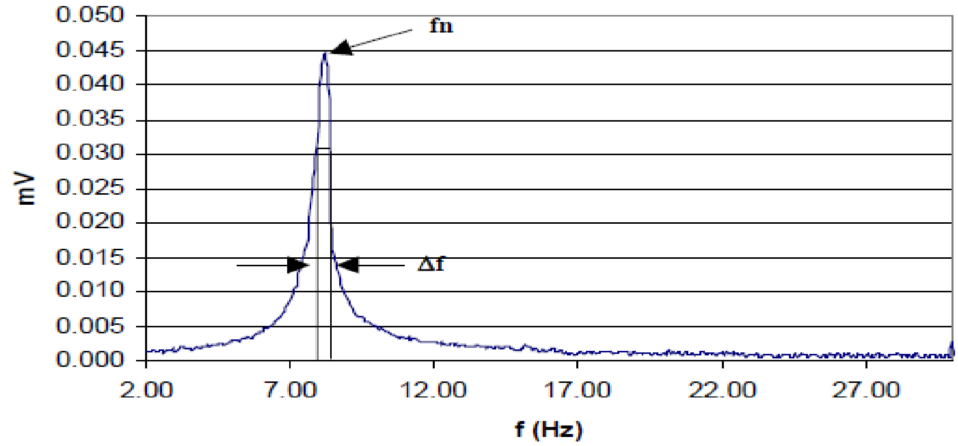

Fig. 4 Measurement of Damping Ratio from Amplitude Spectrum

Therefore the damping ratio can be calculated by the eq. 5 as

$$\zeta = \frac{\Delta f}{f_n} \text{.............}(5)$$

From the damping ratio, logarithmic decrement can be given by the equation

$$\delta = \frac{2\pi\zeta}{(\sqrt{(1-\zeta^2)})} \text{..............}(6)$$

In this paper logarithmic decremented was calculated by half bandwidth method and its values for different fin tube configurations are given in table 2.

Table 3. Natural Frequency and Logarithmic Decrement for Fined Tube

Tube Specification / Modal Parameters	Plain Tube	Fin Tube With 8.466mm Fin Intensity		Fin Tube With 2.822mm Fin Intensity	
		3mm Fin Height	6mm Fin Height	3mm Fin Height	6mm Fin Height
Natural Frequency f (Hz)	49.2	47	46	44.33	41
Logarithmic Decrement δ	0.0128	0.0134	0.0136	0.0141	0.0153

Critical Velocity of fluid flow

Finally using Connors equation given in Eq.1 critical velocity for all tube models was calculated. This critical velocity was under the certain assumption that natural frequency and logarithmic decrement obtained by Ansys are accurate. According to Ziada et. al value of Connors's constant K was 4.05(Ziada, Jebodhsingh, Weaver, & Eisinger, 2005) which was further studied by Desai Pavitran for water as a fluid which varies between 2.95 for plain tube and 4.49 for a finned tube with 10 fpi. In the current study, K was assumed as 4.05. the critical velocity for fluid elastic instability calculated for different fin tube array specifications. Critical velocity is the velocity of fluid flow inside the tube array. To calculate free stream velocity V_f Eq. 1 was used preferred by (Desai & Kengar, 2019) which gives the free stream velocity of water required for the experimental setup.

$$V_f = \left(\frac{p-D_{eff}}{p}\right) V_c \text{..................}(7)$$

Free stream velocity and critical velocity of at instability for finned tubes with different fin pitch are as given in Table 4

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Table 4: Critical Velocity and Free Stream Velocity of finned tube array with different fin geometry

Base Tube Diameter D_b (mm)	Fin tube Diameter D_{eff} (mm)	Fin Intensity p_f (mm)	Effective Diameter of the tube D_{eff} (mm)	Critical Velocity V_c (m/sec)	Free Stream Velocity V_f (m/sec)
19.05	-	-	19.05	14.347	6.308
19.05	25.05	8.4667	19.40	14.79	6.35
19.05	25.05	2.8222	20.11	15.66	6.3976
19.05	31.05	8.4667	19.76	15.48	6.48
19.05	31.05	2.8222	21.18	17.31	6.5289

IV. DISCUSSIONS

The obtained results show Table 5 Consist the value of Free stream velocity, Gap velocity, Natural frequency, Critical Reduced Velocity, Mass Damping Parameter and k values of plain and finned tubes of different densities and different heights at fluid elastic Instability Point. The critical reduced velocity vs amplitude ratio graph for all plain and finned tubes is representing in Fig.5

Table 5: Results of Normal Square at Pitch Ratio = 1.79

Tube Array	Stream Velocity, V_f (m/s)	Natural Frequency fn (Hz)	Gap Velocity, Vg (m/s)	Reduced Velocity V_g/f_nD_{eff}	$M\delta/(\rho D^2_{eff})$	K Assumed
Plain Tube	6.308	49.2	14.3460	15.3063	0.303966	4.1
3mm -3fpi	6.35	47	14.7917	16.2192	0.336779	4.1
3mm-9fpi	6.3976	46	15.2741	16.8048	0.372919	4.1
6mm-3fpi	6.48	44.33	15.8652	17.7939	0.376601	4.1
6mm-9fpi	6.5289	41	17.3059	19.9355	0.475050	4.1

From table 5, it is observed that the critical reduced velocity is rising with the change in fin density as well as fin height also. Here onwards a large change in amplitude response occurs at a very small change in velocity. This can show the FEI threshold of 1.79 for plain tube array in terms of dimensionless reduced velocity parameter. Results obtained also reflect that as comparing the FEI threshold of the plain tube with finned tube arrangement, instability point is at higher reduced velocity for the finned tube. This effect is negligible compared to the effect of increasing no of fins that led to stabilizing the tube array and delays the instability point. It, therefore, concludes that the addition of the fins leads to a delay in the FEI threshold.

Connors 'Stability Map

For all tube arrays, results for critical reduced velocity and mass damping parameter are presented in Tables 5. The graphical presentation of obtained results for tube array (P/D_{eff})=1.76 are shown on Connors Stability Map in Fig.5. The plotting of data on the stability map is based on Connors' equation presented earlier. The stability criteria used for plotting the data is K=4.1 and a = 0.5 [12]. To date, many researchers have used it as a standard of stability for experiments. By the above stability criteria, D is the outer diameter of plain tubes, while the effective diameter def is used to determine the dimensionless instability parameters for fine tubular ranges. Stability Significantly lower speed when plotted on the map and results of mass dumping parameters indicate that the data for the current work is beyond the stability limit. This suggests high volatility limits for all funding pipelines in current experiments. This indicates that the instability entry of the plain range is lower than that of the tube series.

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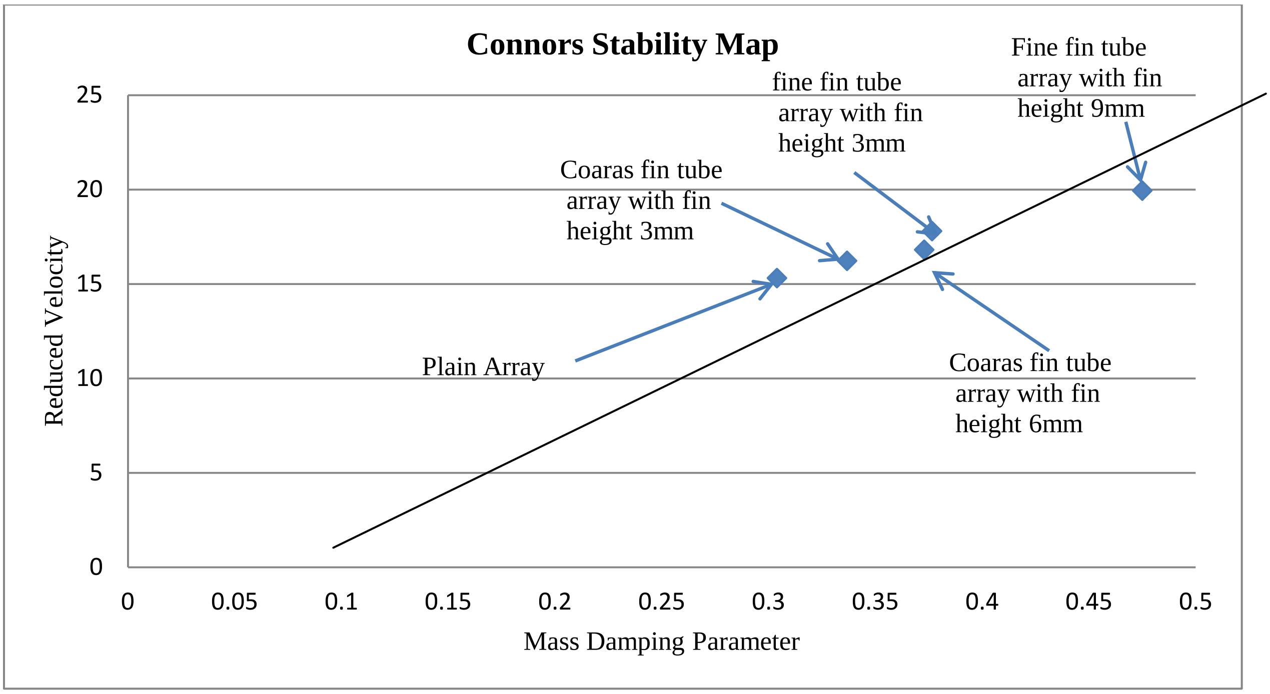

Figure 5: Connors' Stability Map

V. CONCLUSION

The main purpose of this research, as mentioned previously, is to find out critical velocity at instability, to identify the Connors constant for a given condition, and validate theoretical results. The paper has presented the procedure of theoretical calculation with certain assumptions Present work extensively gives an idea about the selection of different parameters with specifications, the study of various fluid properties. This will act as a pathway for new researchers for the study of fluid elastic instability theoretically with the help of different software and previous researchers.

Theoretical calculations based on Connor's equation show that the critical velocity at instability for the finned tube is more than the plain tube. Also, critical velocity goes on increases with an increase in fin height which is similar to the experimental results of (Desai & Maniyar, 2019)(Desai & Kengar, 2019)(Desai & Pavitran, 2017) shows that critical velocity at instability increases with an increase in fin intensity and fin height.
Connors' stability map, which plots non-dimensional parameters on x and y axes, indicates a higher instability threshold for all the finned tube arrays compared to plain tube arrays with the same base diameter and length of the tubes. This phenomenon is similar to TEMA standards.

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