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## Experimental Study of Damping in Tube Bundles with Parallel Triangular Configuration

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### Abstract

Wear and damping analysis of aluminum and brass flexible monitoring tube in parallel triangular tube bundles with a pitch-to-diameter ratio (P/D) of 1.55 subjected to flow-induced vibration (FIV) has been investigated using a low speed closed loop water tunnel. A number of twenty-seven aluminum tubes were used to fabricate the tube bundle. Experimental testing was performed at maximum 0.27 m/sec with three different time spans i.e. 30, 60 and 90 minutes for both brass and aluminum monitoring tubes at a natural frequency of 7, 8, 9, and 10 Hz. A test section of 200 mm × 100 mm in size was prepared by using acrylic materials, and a 10 HP centrifugal pump was used to maintain a flow of 0.27 m/s. The test tubes had an outer diameter and length of 12.7 mm and 228 mm respectively. Data acquisition and spectral analysis were performed using node commander and Sigview software, where a G-Link tri-axial accelerometer captured vibration responses during testing. A SEM analysis was used to calculate the wear score of both flexible tubes at different natural frequencies and different time periods. The results revealed that the maximum wear score was found on aluminum monitoring tube at 7 Hz natural frequency. Where, the most stable damping behaviour was also found at 7 Hz. The damping ratio accuracy increased with decreasing natural frequency. Brass monitoring tube consistently showed a 33.34 % of higher damping ratio compared to aluminum at 7 Hz frequency. The SEM analysis confirmed more severe surface degradation in aluminum as compared to brass tube. The wear score behaviour of aluminum monitoring tube was found 27.71% greater as compared to brass monitoring tube at maximum time period 90 minutes. Overall, this research provides new insight into enhancing damping performance and durability in shell-and-tube heat exchangers used in nuclear, process, and thermal systems.

**Keywords:** Flow-Induced Vibrations (FIV), Parallel Triangular Tube Bundles, Brass Support Plate, Damping Characteristics

### 1. Introduction

Flow Induced Vibration (FIV) represents a significant challenge for shell and tube heat exchangers (STHX's), nuclear steam generators, and other thermal hydraulic systems where fluid structure interactions induce tube oscillation, wear and eventual mechanical failure of components [1-2].



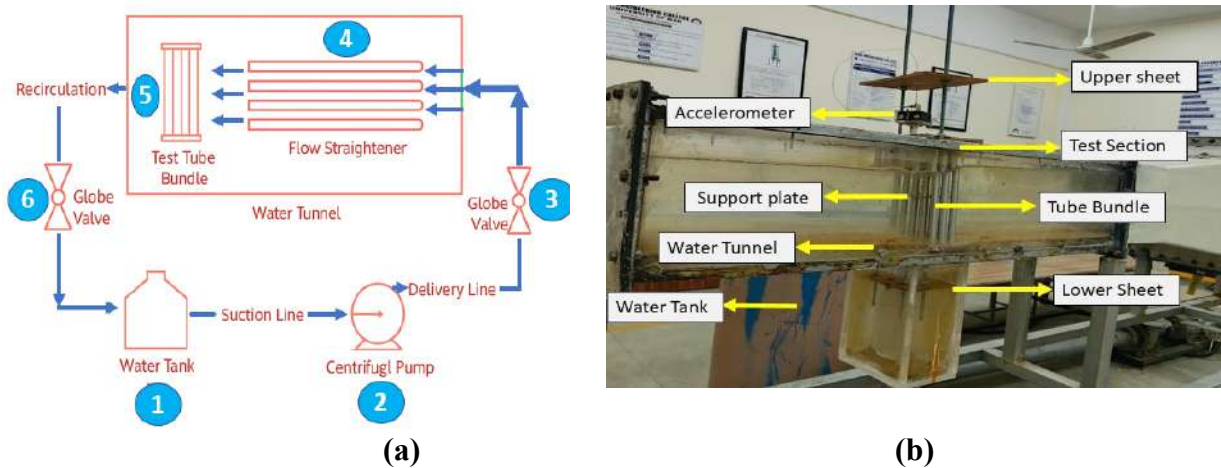
STHX's are commonly used in many industries i.e. HVAC, chemical and nuclear industries [3]. Support plates (baffles) help the fluid for proper flow and also helps the tubes for the increase of thermal efficiency and structural integrity. As fluid enters a tube bundle, the onset of a time-varying pressure field causes vibrations, which can lead to fretting wear, fatigue, or structural failure when the system is operated for an extended period of time [4,5]. The severity of these vibrations is dependent on the damping properties of the tube material as well as the surrounding fluid environment [6-9]. Wear scar phenomenon was started to explore in 1970's especially in shell and tube heat exchangers [10]. These studies have valuable information for better and in depth understanding of scar mechanisms. Wear of tubes resulting into thinning of tubes which losses the structural integrity of the shell and tube heat exchanger [11-14]. Therefore, the understanding of wear phenomenon in shell and tube heat is necessary to prevent the heat exchanger from failure. Damping (which consists of squeeze film damping and frictional damping) plays a key role in the dissipation of vibrational energy, as well as keeping the tubes stable. Prior studies [15-19] suggest that damping effectiveness depends on the damping coefficient, geometry, pitch-to-diameter (P/D) ratio, and the mechanical properties of the material. Materials with higher stiffness and density are typically more stable with respect to vibration, and have a lesser response amplitude. However, lighter materials, like aluminum are exceptional for structurally light components, but have higher levels of displacement and deterioration due to a lesser damping capacity and softer mechanical properties.

The current study is aimed at understanding the influence of damping behavior on vibration and wear performance, of both brass and aluminum tube materials. In a low-speed, closed-channel, water tunnel, brass and aluminum tube materials were arranged in parallel, triangular tube bundles  $P/D = 1.55$ . A G-Link tri-axial accelerometer was used to assess the dynamic response at natural frequencies 7, 8, 9, and 10 Hz. Damping ratios and wear was studied over time at 30, 60, and 90minutes intervals. The surface topography using scanning electron microscopy (SEM) was also investigated for all given natural frequency at all time periods. This study showed that the wear of aluminum tubes was % greater as compared to brass monitoring tube and damping characteristics of brass tubes was % higher as compared to aluminum tubes under 7 HZ of natural frequency and 90 minutes of time duration, respectively. These results provide useful design considerations for the use of heat exchangers, where diminished wear and enhanced damping could improve operational life and reliability.

## 2. Experimental Setup

The experiments were conducted on a low-speed closed-loop water tunnel developed by the Flow-Induced Vibration Research Group at Wah Engineering College, University of Wah, Wah Cantt. The test section had a size of  $200 \times 100$  mm and was fabricated from acrylic plates, purchased from local market of wah cantt, Pakistan. The low speed closed loop water tunnel consist of a converging and diverging metallic portion. A 10 HP centrifugal pump and a 200-gallon storage tank was used

to maintain the circulation of water. The flow velocity in the test section was controlled through main and bypass valves and was measured using Doppler ultrasonic flow. The flow was maintained at 0.27 m/s. The natural frequencies of the monitoring tube in a bundle were range from 7 to 10 Hz. This test setup represented the cross-flow conditions around the tube bundles. A G-Link tri-axial accelerometer was attached to the monitored tube to measure the vibration responses in the streamwise and transverse directions. The data was recorded using node commander software and was subsequently analyzed with Sigview to evaluate the frequency spectrum. Figure 1 presents the schematic and test section of closed loop low speed water tunnel.



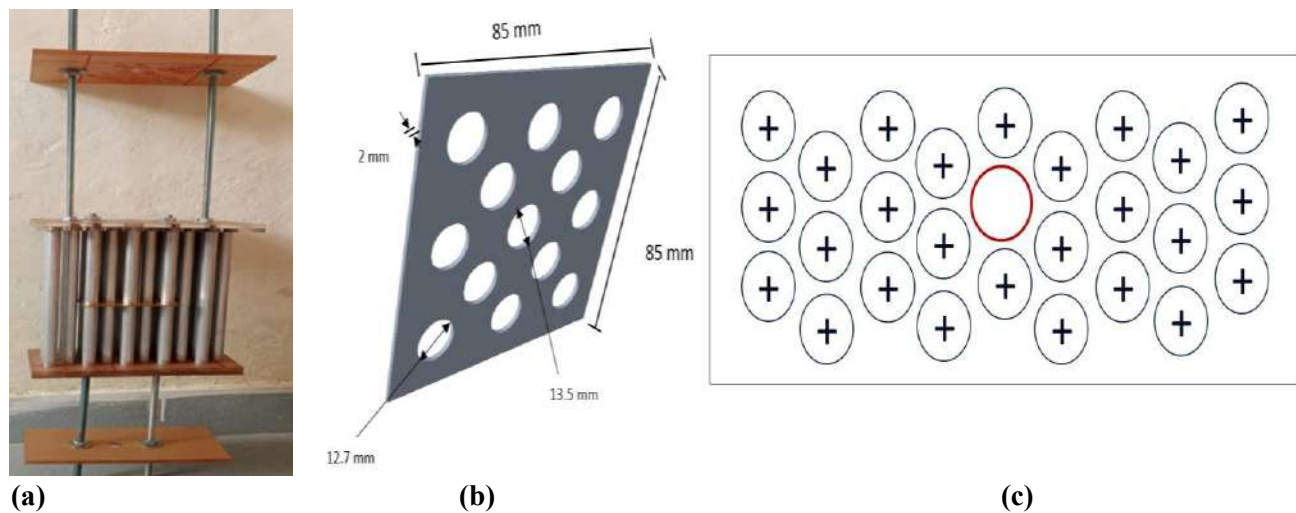
**Fig.1. (a) Schematic diagram of Experimental Setup (b) Closed Loop Water Tunnel**

### 2.1 Tube Bundle Configuration and Test Measurement procedure

A parallel triangular tube bundle with 1.55 P/D was developed using a flexible monitoring tube of aluminum and brass at the center of a tube bundle, surrounded by rigidly supported tubes to maintain boundary stability. The flexible tube was pre-tensioned with a 0.2 mm diameter piano wire to manifest the desired natural frequencies tested of 7, 8, 9, and 10 Hz. The support plates were made of acrylic and were 200 × 90 mm in size and 1.5 mm thick to accommodate precise alignment and structural stability of the tube-bundle. To study the effect of material properties on damping behavior and wear under the same flowing conditions, two materials (Aluminum and Brass) were selected for the investigation. Both tube sets shared the same geometries: outer diameter 12.7 mm, inner diameter 11.7 mm, and length 228 mm, to ensure they had the same hydrodynamic and structural properties. The material properties and physical properties of both materials are summarized in table 1. The tube bundle with brass support plate at the center of bundle is shown in figure 2.

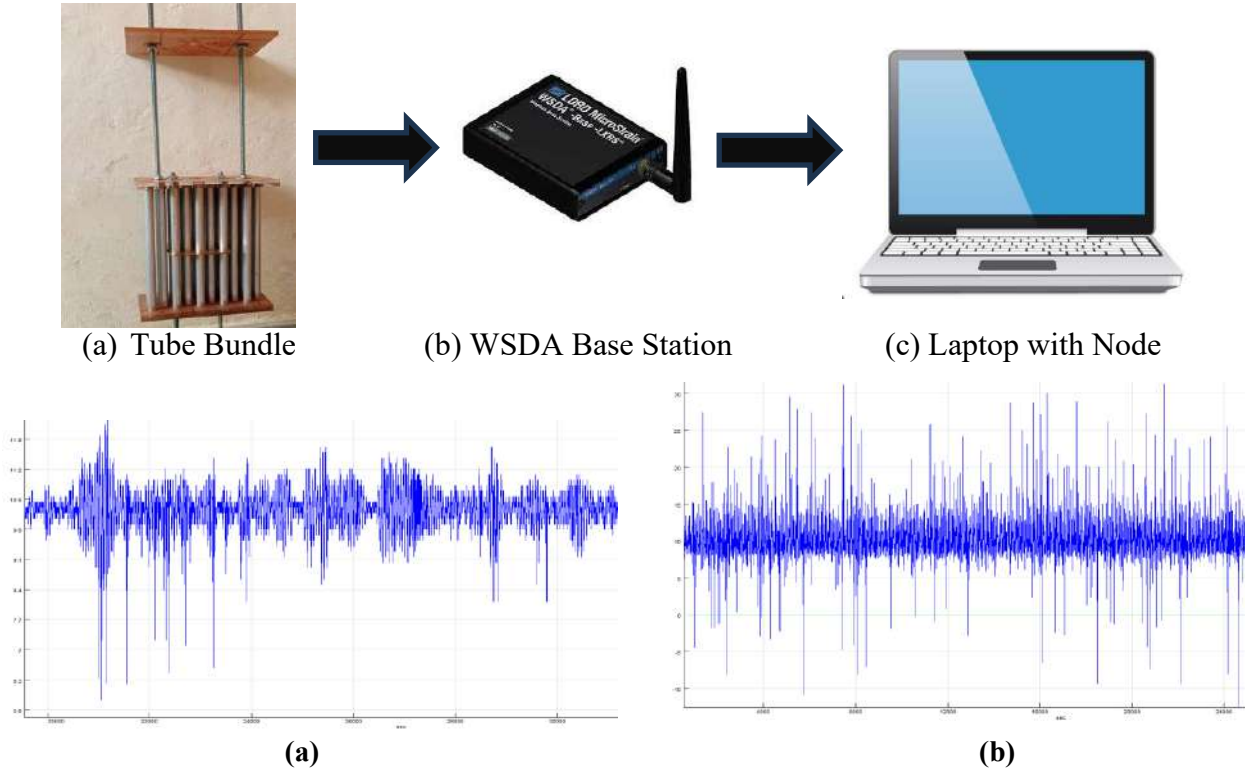
**Table 1.** Specifications of Tube Bundles

Parameter	Specification	
Tube material	Aluminum	Brass
Number of tubes	30	12
Type of tube arrangement	Triangular	Triangular
Mass of tube	5.14 g	56.14 g
P/D ratio	1.55	1.55
Outer / Inner diameter	12.7 mm / 11.7 mm	12.7 mm / 11.7 mm
Tube length	228 mm	228 mm
Modulus of Elasticity	69,000 MPa	110,000 MPa
Baffle thickness	1.5 mm	1.5 mm
Density of water	999.9 kg/m <sup>3</sup>	999.9 kg/m <sup>3</sup>
Tube-to-baffle radial clearance	2.3 mm	2.3 mm



**Fig. 2.** (a) Tube Bundle (b) Support Plate (c) Schematic diagram of triangular tube bundle arrangement.

The flow-induced vibration studies on both pipe materials were conducted under the same conditions with a fixed flow velocity of 0.27 m/s to test for time duration of 30, 60 and 90 minutes. A G-Link tri-axial accelerometer was placed on the flexible tube in order to record the vibration signals, which were processed in node commander and later analyzed in Sigview to produce damping ratios. The surface of the tubes were examined by scanning electron microscopy (SEM) focusing on wear morphology, surface degradation, and material loss after each time duration. For the Data Acquisition stage, subsequent to all in-field vibrations response were captured, a graphical representation followed Figure 3 (a) shows the vibration signal for Aluminum, while Figure 3(b) shows the signal for Brass with contrast in both amplitude and damping behavior of both materials.



**Fig. 3 (a) Aluminum Vibrational Signal (b) Brass Vibrational Signal**

## 2.2 Fluid-Elastic Model

The varying behavior of tube bundles and controlling fluid flows relates to the complex construction of tube bundles. The currently adopted model is used for the tube-support configuration with frictional damping behavior. The damping ratio is expressed in relation to the number of spans,  $N$ , support plate thickness,  $t$ , and span length,  $L$  as:

$$\zeta = 5 \left( \frac{N-1}{N} \right) \left( \frac{t}{L} \right)^n \quad 1$$

This model successfully captures the effect of geometrical and contact parameters on the overall damping performance. This model is ideally suited for low frequency vibration range from 7 to 10 Hz. Both the tubes tested at constant flow velocity of 0.27 m/sec for 30, 60, and 90 minutes to investigate the wear and vibration response.

$$\zeta = \frac{f_2 - f_1}{2f_n} \quad 2$$

where  $f_n$  is the natural frequency at maximum amplitude, and  $f_1$ ,  $f_2$  are the frequencies.

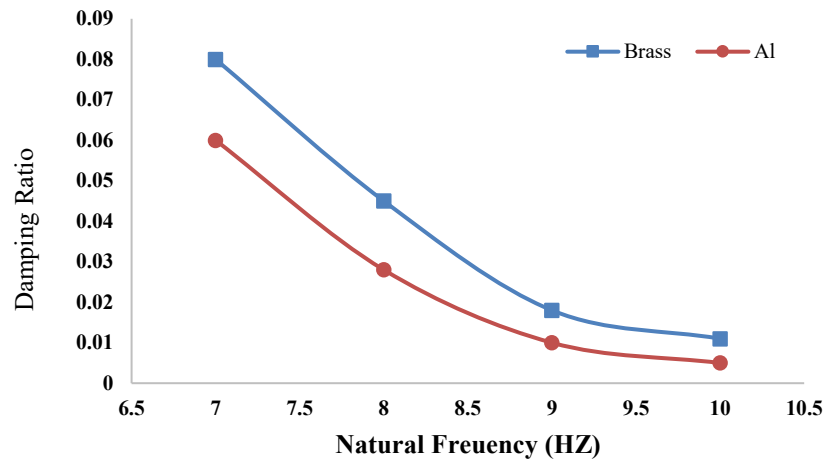
### 3. Results and Discussion

#### 3.1 Damping Behavior

Damping ratios for the brass and aluminum tubes were analyzed at the natural frequencies of 7, 8, 9, and 10 Hz. The relationship between frequency and damping ratio is given in table 2. Figure 4 presents the effect of natural frequency on damping ratio for both monitoring tubes in a tube bundle.

**Table 2.** Damping Ratio Values for Brass and Aluminum Tubes

Frequency (Hz)	Brass ( $\zeta$ )	Aluminum ( $\zeta$ )
10	0.011	0.005
9	0.018	0.010
8	0.045	0.028
7	0.080	0.060



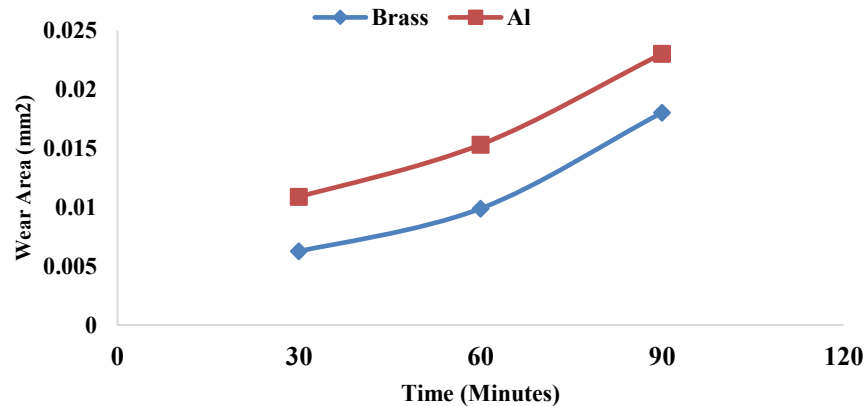
**Fig. 4.** Effect of Natural Frequency on Damping Ratio in Brass and Aluminum Tube Bundle

The damping ratio rises with a decrease in natural frequency, in the case of both materials indicating that more energy is dissipated at a lower frequency owing to increasing viscous and frictional effects. The damping ratio of brass was consistently higher than that of aluminum, consistent with brass's superior capability to dissipate vibration energy. Brass monitoring tube consistently showed a 33.34 % of higher damping ratio compared to aluminum at 7 Hz frequency.

#### 3.2 Wear Area Progression

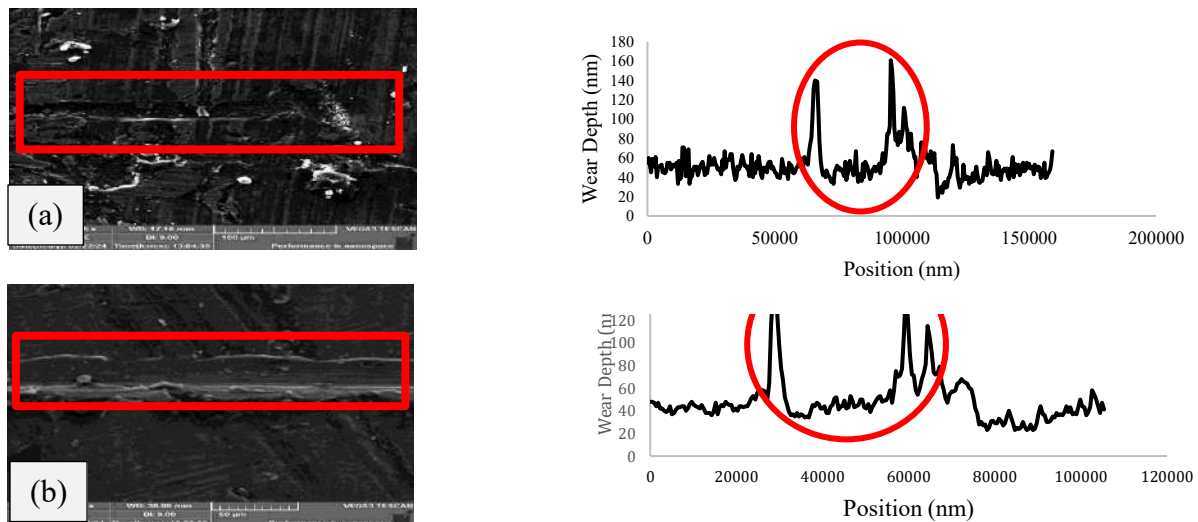
Wear scar behaviour of Aluminum and brass monitoring tube has been investigated using SEM analysis. Aluminum flexible tube exhibited higher wear scar area and lower damping capacity resulting in higher amplitudes of vibration and a greater number of contacts with the baffle plate.

Aluminum monitoring tube has exhibited 27.71% greater wear scar area compared to brass monitoring tube at 7 Hz natural frequency as shown in figure 5. The relationship between time period and wear area for brass and aluminum monitoring tubes is shown in figure 5.



**Fig. 5.** Progression of Surface Wear Over Time for Brass and Aluminum

SEM analysis further supported these findings where, aluminum tubes exhibited surface wear scar while brass tubes showed only minor abrasion on surface and maintained better surface integrity. These findings confirm that materials with higher damping and stiffness dissipate vibrational energy more effectively, reducing mechanical wear and improving durability. Figure 6 presents the surface morphology testing of both brass and aluminum monitoring tubes using scanning electron microscope.



**Fig. 6.** Scanning electron microscope (SEM) images (a) Brass flexible tube (b) Aluminum flexible tube



#### 4. Conclusion

This study investigated the damping characteristics and wear performance of brass and aluminum tubes in a parallel triangular tube bundle ( $P/D = 1.55$ ) under flow-induced vibration (FIV) conditions at natural frequencies of 7, 8, 9, and 10 Hz. The experimental findings indicated that the around 7 Hz frequency exhibited the most stable damping performance, and damping ratio had an inverse relationship with the natural frequency. Brass monitoring tube consistently showed a 33.34 % of higher damping ratio compared to aluminum at 7 Hz frequency, which indicates that brass tubes can dissipate vibrational energy more rapidly, producing a higher level of vibrational stability. Aluminum monitoring tube has exhibited 27.71% greater wear scar area compared to brass monitoring tube at 7 Hz natural frequency. SEM images validated these findings wherein the aluminum tube surfaces showed evidence of plastic deformation, while the brass tube surfaces exhibited superior condition after prolonged exposure under the FIV conditions.

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