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The Effect of Change in Flowrate on Power Spectral Density (PSD) of Automotive Radiator System for Flow-Induced Vibration Monitoring

N F D Razak[1], M S M Sani[1,2*], W H Azmi[1,2] and B Zhang[3]

[1]Advanced Structural Integrity and Vibration Research (ASIVR), Faculty of Mechanical Engineering, Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia
[2]Automotive Engineering Centre (AEC), Universiti Malaysia Pahang, 26600 Pekan, Pahang, Malaysia
[3]School of Mechanical Engineering, Ningxia University, 750021 Yinchuan, China

[*]Corresponding author: mshahrir@ump.edu.my

Abstract. The dynamic motion of internal fluid flow caused an interaction between the fluid's dynamic forces and a structure's inner wall. This phenomenon will induce unstable vibration into the system and recently called flow-induced vibration. In this study, an experimental analysis was performed to identify the changes in the characteristics of vibration measured on an automotive radiator resulting from internal flow in a circular heated tube. The vibration result is presented in terms of Power Spectral Density (PSD) that shows the strength of the energy variations as a function of frequency. Water was used as the working fluid operate with engine temperature range from 80 to 90 °C. The air flow velocities of radiator cooling fan were varied from 1.0 to 1.9 m/s and the water flowrates were 2.2, 2.8, 3.2 and 3.8 l/min. Experimental results are presented and indicated that PSD values are dependant to the fluid flowrate. It is also analysed that relationship between vibrations (PSD) and flowrate is influenced by the change of radiator cooling fan speed. Apart from that, the paper also develops a set of vibration features that will assist in identifying low flow conditions in automotive radiator.

1. Introduction

Recently in automobile industry, there is an increasing issue in vibration monitoring for implications on comfort perceived by human inside and outside cars [1]. A typical automotive cooling system, consists of a radiator and its cooling fan are considering as a rotating machine that has a distinctive characteristic vibration frequency spectrum [2]. The form of the frequency spectrum and peaks appearance at specific frequencies will change and are indicative of faults associated with the machine. Several factors that make the task of recognizing the fault become more complex are the presence of multiple faults, noise, fault severity, geometry of the machine, change of speeds and operating conditions.

Vibration waveform is most commonly viewed in the frequency domain resulting from the Fast Fourier transform of the time series data [3]. In sensing technology, there are many sensors have been introduced in recent developments that guarantee high performance for both static and dynamic measurements. Furthermore, the sensors can be used to perform post-processing computations on the acquired digitalised signals with enclosed signal processing units [4-6]. Moreover, the vibration levels will increase by the excitation of hydraulic and mechanical forces. Hydraulic forces are excites from hydraulic imbalance, internal recirculation, suction, cavitation, vane passing forces, and discharge recirculation, rotating stall, surge and system instabilities while mechanical forces include resonance, mechanical imbalance, and conditions resulting from pump installation, wear and assembly [7].

Other than considering the radiator cooling fan as a major contributor to vibration in vehicle, the flow induced vibration now considered important factors in the entire vehicle design process. Regarding this matter, internal fluid flow inside the piping system which causes vibration to induce due to the interaction of fluid forces and structure inner surface has been investigated by various researchers using numerical, experimental and analytical approaches [8-14]. The vibrations is generated by fluid motion that involves the reactions of fluids and solids to stresses imposed by time-varying flow [15]. In order to develop operating regulation, identification of characteristics from the vibration signal that identify low flow conditions could be used. Therefore, an excellent foundation on which preventive and corrective maintenance programs can be designed by vibration spectrum analysis provided [16, 17].

In this case study, Power Spectral Density (PSD) that shows the strength of the energy(power) variations as a function of frequency is presented where PSD shows at which frequencies variations are strong and at which frequencies variations are weak. In the previous researches, the sensitivity of PSD and the dynamic response of structures can be obtained by pseudo-excitation method (PEM) with respect to the damage parameters that are obtained using stationary and random excitation. This method is high-efficiency for calculating power spectral density of structural dynamic responses [18-20].

Overall, this work aims to develop guidelines that can be used for vibration analysis and advancement by process engineers to implement satisfactory operating flow ranges for their existing equipment. Data was collected and processed with commercially available software and transducers. Other than that, it is to emphasize the role of experimental activity in identifying possible vibration generation problems, which could affect vehicle overall harmony.

2. Experimental apparatus and procedure

The test facility, shown in Figure 1, consists of a car radiator (test section), coolant tank with heater, water pump with control valve, pressure transmitter, cooling fan with motor speed regulator, flow meter, accelerometer, vibration and temperature signals data acquisition system, and temperature sensor. The schematic diagram of experimental facility to study the PSD of automobile radiator shown in figure 1 below:

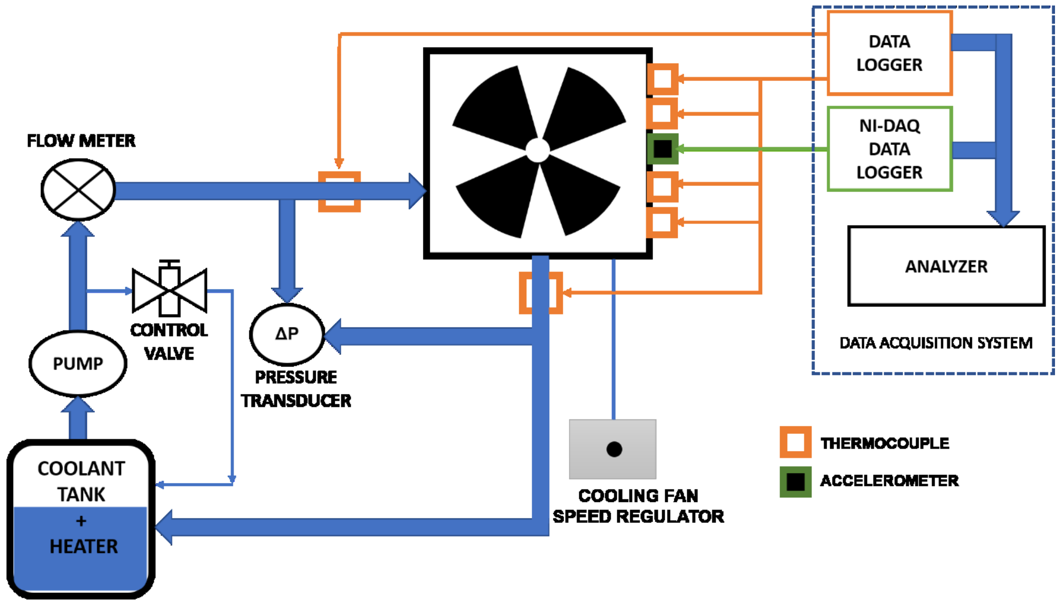

Figure 1. Schematic diagram of experimental setup

2.1 Radiator system (test section)
The test section is a conventional aluminium car radiator and its dimensions are 34.0×1.3×36.8 mm. It was consisted of 32 vertical aluminium tubes. The gap between the tubes is filled with thin perpendicular louvered fins as shown in the figure 3(c). Air was forced to flow through the fins of the radiator using a conventional forced draft fan in the range of 700 to 800 rpm. The radiator cooling fan is made up of an electric motor with flange-mounted fan wheel. The cooling fan and its motor are mounted behind the radiator. Due to the air flow produced, the cooling fan withdraw heat from the coolant.

2.2 Water loop system
In order to eliminate the adverse effect of impurities in the cooling system, purified and distilled water was used as the working fluid (coolant). Figure 2 below shows a complete radiator test rig for vibration analysis. Both ends of the test section (radiator) were connected to a transparent flexible hose, and it would only slightly disturb the vibration motion. The condensed temperature water around 80 to 90 °C was extracted from the water tank using a centrifugal pump and can be precisely adjusted using a bypass valve. The flowrates were set as 2.2, 2.8, 3.2 and 3.8 l/min respectively. The heated fluid was finally chilled in the radiator then fed into the water tank.

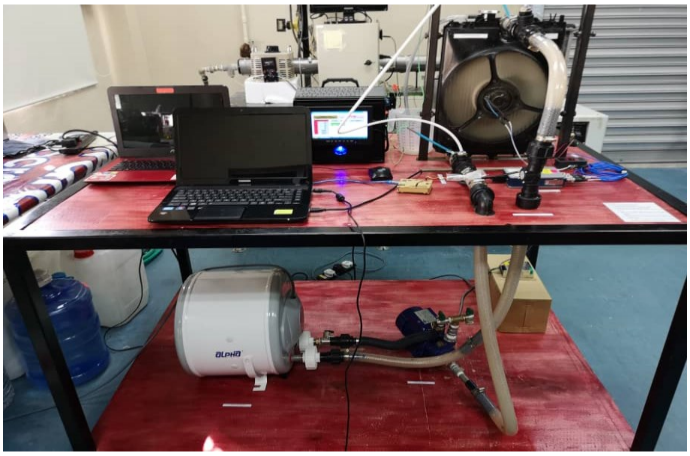

Figure 2. Automotive radiator test rig.

It is important to observe the formation of small bubbles which had an undesirable influence on the fluid flow, especially at the beginning of the experiment. Therefore, there were two solutions that could be implemented. The first solution is by increased quickly the velocity before the test is conducted to eliminate the residual air bubbles inside the pipe as much as possible. The second solution by raising the height of the flexible hose at the inlet of test section. The inlet bubbles would be stop from getting into the heated section. In both solutions, the bubbles could be effectively eliminated. The water loop system was thus made suitable for the experiment.

2.3 Temperature acquisition and measurement
The coolant temperature is measured by using two K-type pointed thermocouples at the predrilled holes located at inlet and outlet pipe of the test section as shown in Figure 3(a) and 3(b) respectively. Only a slight disturbance to the bulk fluid flow occurred from the quick-response temperature probe that had a small volume. Other than that, four K-type thermocouples are used to measure the mean surface temperature as that were firmly attached to the radiator surface shown in Figure 3(c). It should be noted that the temperature acquisition system was not greatly affected in the experiment because the thermocouple acquisition response frequency is far less than the vibration frequency of the test tube influenced by its material time constant which is the response speed while measuring the temperatures. Thus, the time intervals of the test conducted are always longer than 10 min for various vibration or

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fluid flow conditions. In the experiments, the temperatures were measured and accumulated using the data acquisition system and recorded into a computer.

(a) (b) (c)

Figure 3. (a)Inlet pipe of radiator, (b)Outlet pipe of radiator, (c)Radiator surface

2.4 Vibration device setup
This case study is performed by using numerous tools and devices and each tool and device have its own function and specification. A tri-axial accelerometer sensor that attached to the test section shown in Figure 4 used to measure automobile acceleration hence measure the vibrations on radiator surface. Figure 5 show another device that were used in this analysis which is NI Acoustic and Vibration Data Logger to measure the data produce from the accelerometer sensor in order to run the data acquisition using ME'ScopeVES software.

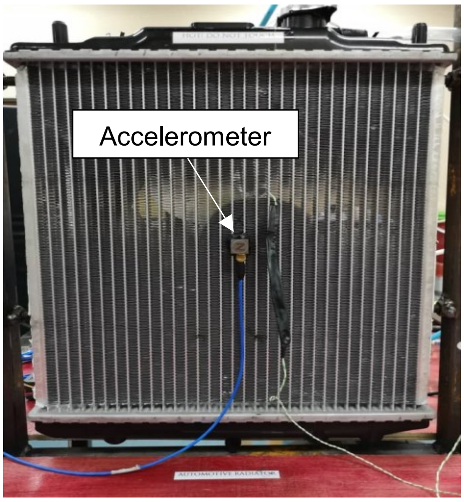

Figure 4. Tri-axial accelerometer

Figure 5. The NI Acoustic and Vibration Data Logger

3. Result and Discussion
All presented spectra are averages of four measurements of each cooling fan speed variations. The frequency range of analysis is limited to 500 Hz as in the higher frequency range, the interaction between coolant flow and vibrations is small. Each spectrum presented in the figures below corresponds to the vibrations excitations, which was induced by a different internal fluid flow rate through the test section

and external flow of air by its cooling fan. It is shown how the amplitude of the chosen frequency range depends on both internal and external fluid flow through the test section.

PSD results show at which frequency variations have strong vibrations and at which frequency variations are weak vibrations. Figure 6 shows frequency range around 360 Hz have stronger PSD value than frequency range around 230 Hz. In the lower frequency range from 209 to 215 Hz as shown in the zoom area, the visible highest spectrum peak of PSD is $1.6x10^{-5}$ m^2/s^3 by the highest flowrate which is 3.8 l/min. It is clear that higher flowrate generates higher level of vibrations.

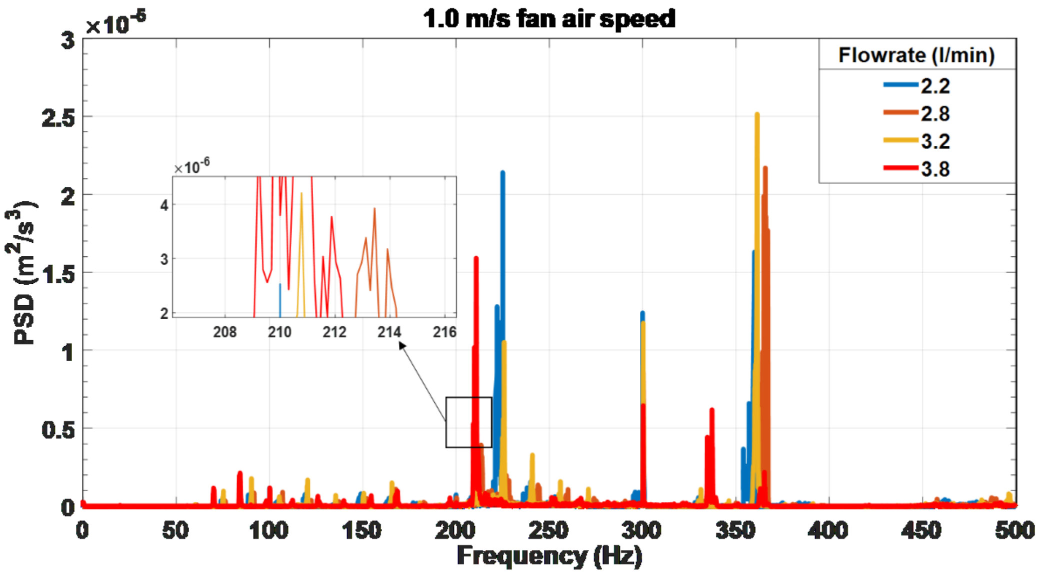

Figure 6. PSD value comparison of various flowrates for 1.0 m/s radiator cooling fan air speed.

Based on the spectrum presented, PSD and flowrate are exponentially dependent [21]. Even though, in the high frequency range from 350 to 370 Hz, vibration is most effectively generated when the flowrate is 3.2 l/min.

Next, each spectrum presented in Figure 7 also corresponds to the vibrations induced by a fluid flow through the test section. By increasing the cooling fan speed up to 1.2 m/s of its air velocity, the spectrum peak occurred only at frequency range around 210 Hz. It can be seen, 3.2 l/min of flowrate efficiently generates the highest PSD value which is $1.68x10^{-3}$ m^2/s^3. Almost vibrations amplitudes are stable and reach lower amplitude value in the frequency range below 200 Hz and above 220 Hz for all of four flowrate variations. The frequency resolution already enhanced from 204 to 214 Hz frequency range to get a better data representation between the spectrum peaks.

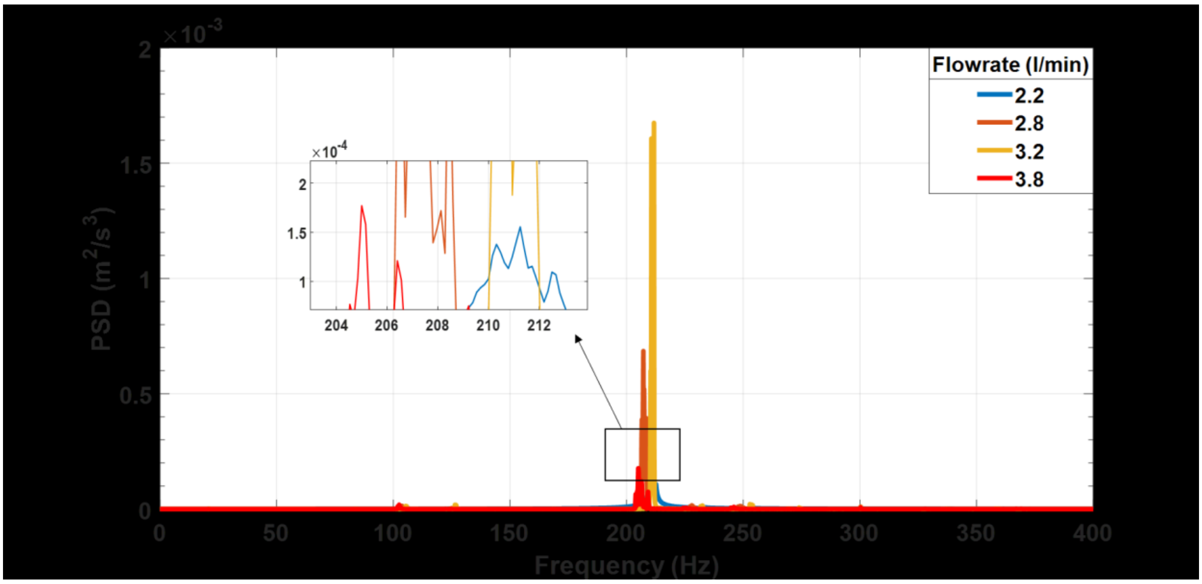

Figure 7. PSD value comparison of various flowrates for 1.2 m/s radiator cooling fan air speed.

Based on the measured results presented, the lowest spectrum peak occurs at the lowest flowrate level at 2.2 l/min. By increasing the fluid flow up to 2.8 l/min the vibration amplitude increased for additional $0.5 x 10^{-3}$ m^2/s^3. Vibration level increased for over $1.0 x 10^{-3}$ m^2/s^3 in this frequency range when the flowrate level is 2.8 l/min and this level shows vibration are most effectively generated as its spectrum reach the highest peak of PSD. However, the amplitude suddenly decreased to the lowest spectrum peak when the fluid is flow at maximum level of flowrate, which is 3.8 l/min. This indicates, the interaction between 3.8 l/min of fluid flow and the inner radiator surface not generated enough energy to induced vibrations in this frequency range.

Figure 8 below shows all the spectra presented when the cooling fan speed is increased up to 1.5 m/s of its air velocity. It can be seen, the strongest spectrum of PSD value for all of flowrate variations occurs in the frequency range around 270 Hz while the weakest spectrum occurs at around 215 Hz frequency range. This clearly indicates that the interaction between fluid flow and the inner radiator surface efficiently generated enough energy to induce vibrations at around 270 Hz frequency range. Almost vibrations amplitudes are stable and reach lowest PSD value in the frequency range above 340 Hz for all of four flowrate variations.

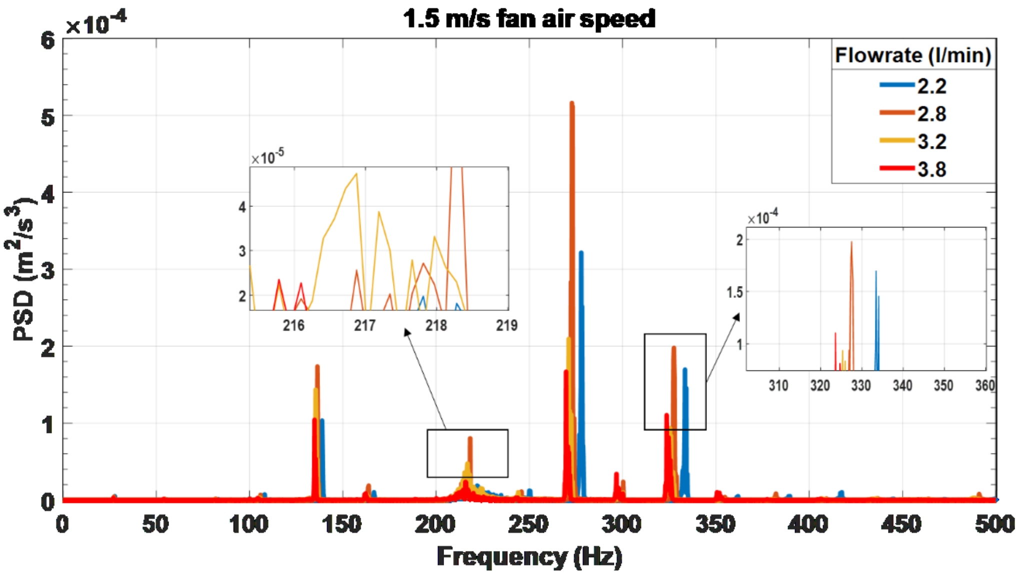

Figure 8. PSD value comparison of various flowrates for 1.5 m/s radiator cooling fan air speed.

Such a result in the diagram above clearly indicates that the dynamically of fluid flow generated vibrations is strongly influenced by 2.8 l/min flowrate visible as the highest spectrum peak at each frequency ranges. By referring to the zoom area, the frequency ranges from 216 to 219 Hz presented the lower spectrum part.

Each spectrum presented in Figure 9 also corresponds to the vibrations induced by a fluid flow through the test section. By increasing the cooling fan speed up to maximum level around 1.9 m/s of its air velocity, the highest spectrum peak occurred at frequency range around 170 Hz influenced by 3.2 l/min of fluid flowrate. It is efficiently generated the highest PSD value of $5.6x10^{-4}$ m^2/s^3. Almost vibrations amplitudes are stable and reach lower amplitude value in the frequency range above 400 Hz for all of four flowrate variations. For better data analysation between the spectrum peaks, the frequency resolution already enhanced for frequency range around 170 and 340 Hz.

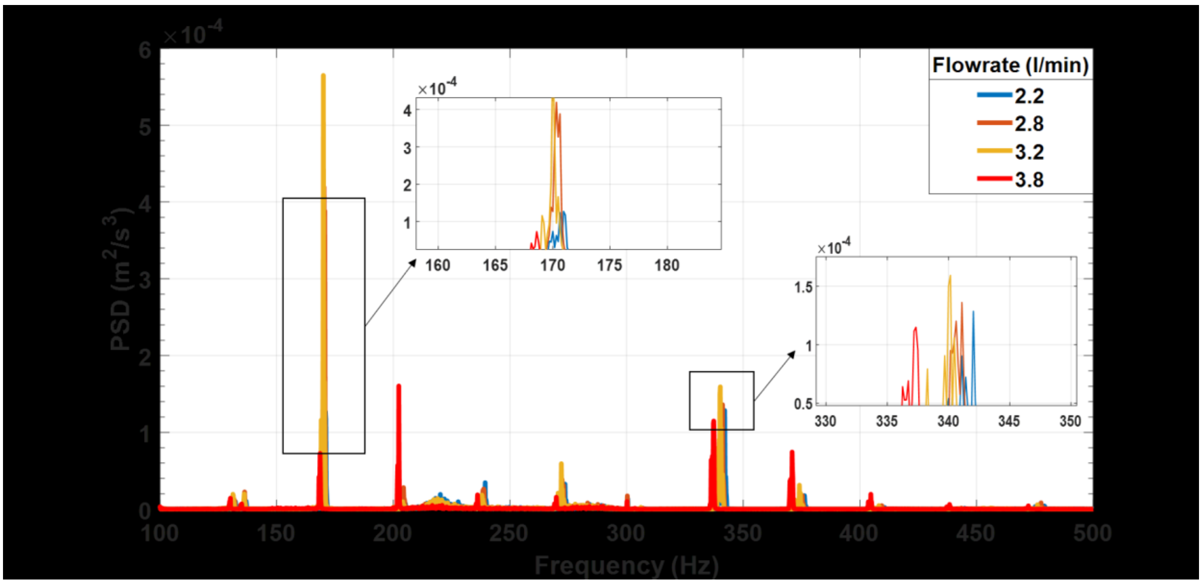

Figure 9. PSD value comparison of various flowrates for 1.9 m/s radiator cooling fan air speed.

In zoom analysis, the lowest spectrum peak visible when fluid is flow at highest flowrate level which is 3.8 l/min for both 170 and 340 Hz. At lowest flowrate level, 2.2 l/min generated vibrations 5.4×10^{-5} m^2/s^3 more than at 3.8 l/min for 170 Hz and 1.4×10^{-5} m^2/s^3 more for 340 Hz. By increasing the fluid flow up to 2.8 l/min the vibration amplitude increased for additional 2.9×10^{-4} m^2/s^3 in 170 Hz and 0.76×10^{-5} in 340 Hz. Vibration level increased for over 1.0×10^{-3} m^2/s^3 in 170 Hz frequency range when the flowrate level is 3.2 l/min and this level shows vibration are most effectively generated as its spectrum reach the highest peak of PSD.

4. Conclusion

Based on measurement result, vibration data presented in terms of PSD analysis for a range of flow rates from 2.2 to 3.8 l/min has a strong relationship with the fluid flowrates. The internal excitation of the fluid flow inside the automotive radiator influenced significantly to vibration magnitude of the test section surface. Moreover, increasing in the dynamic motion of fluid flow will increase the vibration excitation due to the fluid forces increases. As conclusion, the data mostly showed 3.2 l/min flow rate effectively generated high vibration spectrum than other flow rates where the spectrum peaks are strong at each frequencies variation. It is also analysed that the change of radiator cooling fan speed increases the vibration induced into the system other than fluid flowrate. In future, the advancement of vibration in automotive industry for better and safer radiator can be assisted by this study.

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