Noise and vibration analysis for automotive radiator cooling fan

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Abstract. This paper aims to analyse the noise and vibration of the automotive radiator specifically focused on its cooling fan for different fan conditions and different coolants used namely Ethylene Glycol (EG) water-based and Titanium Oxide (TiO\textsubscript{2}) nanofluid. Noise source identification is carried out by utilizing the sound intensity mapping method while an accelerometer is used to measure the vibration results. Both of these experiments are conducted when the fan was both in static and working conditions. The maximum cooling fan speed for the working fan detected by a tachometer for EG water-based is 1990 rpm while TiO\textsubscript{2} nanofluid is 2030 rpm. The difference in speed is due to the different physical properties such viscosity of each coolant has where TiO\textsubscript{2} nanofluid has lower viscosity than EG water-based. The maximum sound power level produced by EG water-based is 53.73 dB while TiO\textsubscript{2} nanofluid is 101.94 dB. Meanwhile, the vibration frequencies of EG water-based are higher than TiO\textsubscript{2} nanofluid. The noise level increases with the cooling fan speed but decreases with the vibration frequency. Apart from studying the noise and vibration of the automotive radiator, this research also analysed the potential application using nanofluid due to its great properties according to its major use in the heat transfer enhancement. As a conclusion, nanofluid as a radiator coolant could improve heat transfer rate, and could also reduce the presence of vibration in the automotive cooling system.

1. Introduction

A typical automotive engine cooling system consists of a radiator, cooling fan, water pump, coolant reservoir, thermostat, heater core and necessary plumbing for both radiator and heater core. This study had focused on car radiators as heat exchangers that are used diversely in the automotive industry for cooling internal combustion engines. Radiator cooling fan is a device that works to pull the air through a radiator to regulate the engine temperature. However, this operating cooling fan has been known as a major contributor to noise in a vehicle other than the engine. It became more crucial to figure out a solution in reducing this vulnerability according to the unwanted bad effects that gives distraction to the community specifically to the passengers. In consequence to this risk, it is absolutely necessary to conduct a detailed experimental study on noise analysis for automotive radiator cooling fans hence the automotive cooling system. Sound is produced by the vibrating body which the vibrations that propagate through the medium to the listeners and it also such a common part of everyday life [1].

Sound has affected humans in a positive and negative way. In a positive way, sound can be defined as pleasant and relaxing. But the opposite, the unpleasant and unwanted sound is called noise which
occurs in high decibel (dB) frequency [2]. When a source produces sound power (P), it will create a certain sound intensity (I) at a distance away from the source [3]. Noise measuring devices are typically used a sensor such microphones to receive noise signals from the source [4]. Noise source identification (NSI) techniques are used to optimise the noise emission from a wide range of products including vehicles, household goods and wind turbines [5]. Sound waves which consist of a pure tone are only characterised by amplitude, wavelength, frequency and period [6]. Sound transmits at numerous speeds and this movement gradually spreads to adjoining air particles that assist far from the source and depends on the medium [7]. Frequency of sound is the number of pressure difference per second and is measured in hertz (Hz) [8]. Sound source emits power and these results in a sound pressure. Sound power is the cause while sound pressure is the effect [9]. Hearing damage may be caused by high sound pressure [10].

The measure of the total sound energy produced is called sound power, where sound source produces per unit time and free of its surroundings [11]. Sound intensity describes the rate of energy flowing through a unit area. In the SI system, the unit area is 1 m². There will be energy flow in certain directions but not in others because sound intensity gives a measure of direction [12]. Noise is judged to be unpleasant, loud or disruptive to hearing and according to a physics standpoint, noise is indistinguishable from sound, as both are vibrations through a medium, such as air or water [13, 14]. Tones or changes in sound level are the noise features that will make human listen and take notice [15]. Noise can be produced by many sources such as a man's vocal cord, a running engine, a vibrating loudspeaker diaphragm, an operating machine tool and others [16]. The dimensions of a noise source are small compared to the distance to the listener, it is called a point source and sound energy spreads out spherically. So the sound pressure level is the same for all points at the same distance from the source, and decreases by 6 dB per doubling of distance [6]. If a noise source is narrow in one direction and long in the other compared to the distance to the listener, it is called a line source and the sound level spreads out cylindrically. This means the sound pressure level is the same at all points at the same distance from the line, and decreases by 3 dB per doubling of distance [17].

Objective measurements of sound levels are an indispensable part of any environmental noise protection program. The environmental noise levels vary greatly. Noise is often impulsive or contains pure tones [18]. A sound field is a region where there is sound. It is classified according to the manner and the environment in which the sound waves travel [19]. Sound intensity measurement offers several ways of doing this which have considerable advantages over older techniques. Contour plots give a more detailed picture of the sound field generated by a source [20]. Sound intensity measurements normal to the surface are made from a number of equally spaced points on the surface. Same measurement can be used to calculate the sound power over the grid [19, 21]. Noise source identification by using sound intensity mapping was investigated in diesel engines for different engine speed [22]. An experiment carried out utilizing eddy current dynamometer by sound intensity mapping method for the engine speed range of 1500 to 2000 rpm. The noise source of flywheel cover and manifold are presented. It can be observed that the critical cut-off frequency is 1250 Hz. The sound level powers are within 86.42 dB to 96.34 dB in the range of engine speed. The noise level increases with engine speed.

In this paper, noise analysis is focused on the sound intensity mapping method where a grid is directly setup from Hand-held analyser and an accelerometer is used for vibration analysis. The main purpose of this project is to identify the location of maximum noise level and to measure the vibration result from Frequency Response Function (FRF) obtained using different types of coolants which are Ethylene Glycol (EG) water-based (60% water, 40% EG) and Titanium Oxide, TiO₂ nanofluid. Other than study of noise and vibration of an automotive radiator, this research also analysed the potential application of using nanofluid due to its many great properties according to its major use in heat transfer enhancement.

2. Noise, vibration and heat transfer enhancement relations in automotive cooling system
Many applications such as aircraft engines, motorcycles and other application especially in the automobile field use radiators as heat exchangers for internal combustion cooling devices. Coolant is a liquid that circulates through the engine block to absorb the heat from the operating engine, keeping
the engine cool and then flowing into the radiator after reaching high temperatures around 98 °C to lose the heat to the atmosphere. The coolant will return to the engine when its temperature is dropped to ambient temperature and this process will repeat continuously. Engine coolant is usually water-based, but some may also be oil. It is common to employ a water pump to force the engine coolant to circulate, and also for an axial fan to force air through the radiator.

There are two main types of radiator fans which are mechanical and electrical and this research investigation is focusing on mechanical fans. Mechanical fans are belt driven which it’s attached to a pulley that is connected to the crankshaft via a drive belt. The fan pulley will rotate when the crank shaft rotates then the fan will push air through the automobile radiator. Therefore, when the engine operates at high speed, it will contribute to high fan speed. An automobile travels at diverse ranges of speeds. The more power is needed by the engine to generate speed because it increases when it travels faster; hence the cooling process needs to be enhanced. Thus, the velocity of air striking the radiator becomes a crucial parameter during the cooling phenomenon through the fins. Although, different velocity will affect the noise level [23].

It is difficult for circular fans to cover the whole surface area of the radiator that is rectangular in size. It generates lower velocity area at the corners which then resulted in less heat transfer. Therefore, the lower velocity zones will induce the lower noise level zones [24]. The use of nanofluid based coolant and its effect on cooling capacity was found that nanofluid has a higher thermal conductivity than base coolant which is 50:50 ratio between water and ethylene glycol [25]. It is theorized that different thermal conductivity will result in different rates of heat transfer hence affecting the velocity of the cooling fans. The various parameters of coolants including its mass flow rate, inlet and outlet coolant temperature, viscosity and other properties are varied [26]. The equations for friction factor and Nusselt number to relate it with the enhancement of heat transfer for both laminar and turbulent flow conditions have already been derived [27]. The effects of momentum and heat transfer induced effects in assessing the relations between heat transfer and friction factor [28]. The noise of cooling fans can be summarized that many parameters in an automotive cooling system will affect the noise level because when engines run at high values of rpm, the speed of the vehicle will be increased; the heat generated in the parts of the engine will also increase drastically. Hence, at a higher speed the cooling process should also be effective in order to dissipate the heat to the atmosphere. This study does not only is looking for a solution for the enhancement of the heat transfer rate, but also how to improve in terms of noise and vibration of the car radiator.

3. Experimental measurement method
The experimental methodology starts from the preparation of EG water-based and TiO₂ nanofluid coolant in an advance automotive fluid lab, followed by the preparation of acoustic device and setting up the radiator cooling fans. Next, this is followed by setting up the calibration of intensity mapping prop and vibration analysis method. Then, the noise and vibration measurement of radiator cooling fans is conducted in the alternative energy lab. The total sound power is computed and the vibration result is measured.

3.1. Noise analysis contribution by sound intensity
The noise analysis of the car radiator cooling fan in this study was set up properly in the alternative energy laboratory before the experiment is conducted. The hand-held analyser is placed 1 m away from the front side of the radiator according to the standards of noise measurement method as shown in Figure 1. The devices and instruments used in this noise investigation are Brul & Kjaer intensity probe, a laptop, a pair of microphones and a hand-held analyser. Before the experiment of noise source identification is conducted, a rectangular grid was directly set up by taking a photo of the car radiator using the hand-held analyser, where a 4x4 grid system is plotted to define its surface. Then, the sound intensity technique was carried out from the front side of the radiator as shown in Figure 2.
3.2. Vibration device setup
There are numerous tools and devices used to perform this case study and each tool and device has its own functions and specifications. A uniaxial accelerometer sensor shown in Figure 3 is used to measure automobile acceleration hence measuring the vibrations on cars. Figure 4 shows another device that is used in this analysis which is the 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.

4. Results and discussion

4.1. Sound intensity mapping results
Intensity mapping is the contour that explains a more detailed picture of sound field generated by a noise source hence giving a quick overview of the sources in the selected frequency range. The noise measurements are performed in an alternative energy laboratory with less than 20 to 30 dB background noise and are already filtered by the hand-held analyser itself. Contour plot and the sound power level results when the cooling fan is in static condition for EG water-based coolant is shown in Figure 5 and Table 1. Based on the measured results presented, the highest sound power level produced during the experiment is 50.83 dB and is located at point 16. The green colour area where point 16 is located indicates the radiator part that produced the highest noise level while the blue colour area indicates the lowest noise level which at point 3 with 42.61 dB.
Figure 5. Sound intensity mapping when the cooling fan is in static condition for EG water-based coolant.

Table 1. Sound power level for sound intensity mapping when the cooling fan is in static condition for EG water-based coolant.

| Point | Sound power level (dB) | Point | Sound power level (dB) | Point | Sound power level (dB) | Point | Sound power level (dB) |
|-------|------------------------|-------|------------------------|-------|------------------------|-------|------------------------|
| 1     | 44.22                  | 5     | 47.27                  | 9     | 44.00                  | 13    | 48.23                  |
| 2     | 48.06                  | 6     | 43.88                  | 10    | 49.62                  | 14    | 48.24                  |
| 3     | 42.61                  | 7     | 45.13                  | 11    | 47.38                  | 15    | 48.69                  |
| 4     | 45.08                  | 8     | 47.97                  | 12    | 48.69                  | 16    | 50.83                  |

Next, the contour plot of the sound intensity mapping when the cooling fan is working at the speed range from 1970 to 1990 rpm is shown in Figure 6 and Table 2 shows another sound power level data. Based on the measured results presented, the highest sound power level produced during the experiment is 53.73 dB and located at point 12 which is represented by the green colour. The lowest noise level located at point 11 with 34.89 dB and there is no colour present there because the sound power level value is below than 40 dB.

Figure 6. Sound intensity mapping when the cooling fan is in working condition for EG water-based coolant.
Table 2. Sound power level for sound intensity mapping when the cooling fan is in working condition for EG water-based coolant.

| Point | Sound power level (dB) | Point | Sound power level (dB) | Point | Sound power level (dB) | Point | Sound power level (dB) |
|-------|------------------------|-------|------------------------|-------|------------------------|-------|------------------------|
| 1     | 38.62                  | 5     | 50.23                  | 9     | 48.18                  | 13    | 49.73                  |
| 2     | 47.05                  | 6     | 43.38                  | 10    | 45.69                  | 14    | 38.97                  |
| 3     | 45.65                  | 7     | 48.36                  | 11    | 34.89                  | 15    | 39.66                  |
| 4     | 41.37                  | 8     | 49.38                  | 12    | 53.73                  | 16    | 48.11                  |

The contour plot of the sound intensity mapping when the cooling fan is in static condition for TiO$_2$ nanofluid is shown in Figure 7 and another data is shown in Table 3. Based on the measured results presented, the highest sound power level produced during the experiment is 56.48 dB and located at point 13 which is represented by the green colour. The blue colour area where point 8 is located indicates the lowest noise level of the car radiator with 45.46 dB.

![Figure 7](image_url)

Figure 7. Sound intensity mapping when the cooling fan is in static condition for TiO$_2$ nanofluid coolant.

Table 3. Sound power level for sound intensity mapping when the cooling fan is in static condition for TiO$_2$ nanofluid coolant.

| Point | Sound power level (dB) | Point | Sound power level (dB) | Point | Sound power level (dB) | Point | Sound power level (dB) |
|-------|------------------------|-------|------------------------|-------|------------------------|-------|------------------------|
| 1     | 55.82                  | 5     | 53.12                  | 9     | 52.75                  | 13    | 56.48                  |
| 2     | 50.42                  | 6     | 51.85                  | 10    | 54.14                  | 14    | 49.42                  |
| 3     | 48.50                  | 7     | 52.92                  | 11    | 52.62                  | 15    | 50.22                  |
| 4     | 55.42                  | 8     | 45.46                  | 12    | 50.98                  | 16    | 47.61                  |

The contour plot of the sound intensity mapping when the cooling fan is working at a speed range from 2000 to 2030 rpm is shown in Figure 8 and another data is presented in Table 4. Based on the measured results presented, the highest sound power level produced during the experiment is 101.94 dB and located at point 4 represented by the dark green colour. The lowest noise level is located at point 15 with 44.59 dB and there is no colour present because the sound power level value is below 87 dB.

![Figure 8](image_url)
Figure 8. Sound intensity mapping when the cooling fan in working condition for TiO\textsubscript{2} nanofluid coolant.

Table 4. Sound power level for sound intensity mapping when the cooling fan in working condition for TiO\textsubscript{2} nanofluid coolant.

| Point | Sound power level (dB) | Point | Sound power level (dB) | Point | Sound power level (dB) | Point | Sound power level (dB) |
|-------|------------------------|-------|------------------------|-------|------------------------|-------|------------------------|
| 1     | 70.13                  | 5     | 50.66                  | 9     | 58.79                  | 13    | 70.94                  |
| 2     | 92.16                  | 6     | 53.27                  | 10    | 58.28                  | 14    | 49.34                  |
| 3     | 76.43                  | 7     | 69.44                  | 11    | 51.55                  | 15    | 44.59                  |
| 4     | 101.94                 | 8     | 80.09                  | 12    | 81.79                  | 16    | 56.24                  |

Many possibilities that contributed to the car radiator noises such as where the location is nearest to the engine compartment, as well as the belt and pulley of the car cooling system. All the belts are driven by an engine pulley which is connected to the automotive engine. Noise is produced when this belt and pulley system starts to work. A screeching sound is normally heard from the belt and pulley noise and this will happen when the pulley attached to an engine accessory that is starting to freeze up or caused by the drive belt is loosened. Therefore, these noises induced to the highest sound power level.

4.2. Vibration analysis (FRF results)
The data results were taken from the Me’scopeVES software using the curve fitting method. Table 5 shows the FRF result of the radiator when the fan is in static condition and Table 6 shows the results when the fan is in working condition for EG water-based coolant. Most of the peaks range for the static fan is below 20 Hz and the highest peak occurred at 13.3 Hz of its vibration frequency. For the working fan, most of the peaks range is below than 100 Hz and the highest peak occurred at the vibration frequency of 30.2 Hz when the fan is running at maximum speed of 1990 rpm.

Table 5. Operating frequency when the fan is in static condition for EG water-based coolant.

| Mode | Frequency (Hz) | Mode | Frequency (Hz) |
|------|----------------|------|----------------|
| 1    | 3.71           | 6    | 9.84           |
| 2    | 5.31           | 7    | 12.3           |
| 3    | 6.03           | 8    | 13.3           |
| 4    | 7.09           | 9    | 14.5           |
| 5    | 9.39           | 10   | 15.4           |
Table 6. Operating frequency when the fan is in working condition for EG water-based coolant.

| Mode | Frequency (Hz) | Mode | Frequency (Hz) |
|------|----------------|------|----------------|
| 1    | 29.6           | 6    | 60.5           |
| 2    | 30.2           | 7    | 61.3           |
| 3    | 33.4           | 8    | 63.6           |
| 4    | 58.7           | 9    | 66.8           |
| 5    | 59.9           | 10   | 93.3           |

Table 7 shows the FRF result of the radiator when the fan is in static condition and Table 8 shows the results when the fan is in working condition for TiO$_2$ nanofluid coolant. Most of the peaks range for static fan is below 20 Hz and the highest peak occurred at 4.56 Hz of its vibration frequency. For the working fan, most of the peaks range is below than 100 Hz and the highest peak occurred at the vibration frequency of 4.62 Hz when the fan is running at maximum speed of 2030 rpm.

Table 7. Operating frequency when the fan is in static condition for TiO$_2$ nanofluid coolant.

| Mode | Frequency (Hz) |
|------|----------------|
| 1    | 2.65           |
| 2    | 3.27           |
| 3    | 4.56           |
| 4    | 5.27           |
| 5    | 8.33           |

Table 8. Operating frequency when the fan is in working condition for TiO$_2$ nanofluid coolant.

| Mode | Frequency (Hz) |
|------|----------------|
| 1    | 3.45           |
| 2    | 4.62           |
| 3    | 5.70           |
| 4    | 8.13           |
| 5    | 8.74           |

5. Conclusions
Different coolants are used in the automotive cooling system which will result in different engine speeds due to the different properties of the coolants used such as viscosity and thermal conductivity hence influencing the radiator cooling fan speed. When using EG water based coolant, the maximum speed of the radiator fan in working condition detected by tachometer is 1990 rpm while 2030 rpm when using TiO$_2$ nanofluid. The sound power level for TiO$_2$ nanofluid is higher than EG water-based coolant for both fans in static and working conditions. Meanwhile, the vibration result shows TiO$_2$ nanofluid has a lower vibration frequency than EG water-based coolant for both fans in static and working conditions. The maximum sound power level produced by EG water-based is 53.73 dB while TiO$_2$ nanofluid is 101.94 dB. Meanwhile, the vibration frequencies of EG water-based are higher than TiO$_2$ nanofluid. Therefore, the noise level increases with the engine speed but decrease the vibration frequency. The location of the maximum noise level is identified and mostly occurred nearest to the belting and engine system. Overall, results of this study shows that the use of nanofluid as a coolant is not just for improving the enhancement of the heat transfer rate, but also can improve the presence of vibration in automotive cooling system. However, the improvement in noise reduction still need to be studied and improved due to high noise level produced when using nanofluid.
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