

Application of the Fourier Amplitude Sensitivity Test (FAST) to Analyze Thermal Performance of Vehicle Underbody Components

Ashley Lehman, Vesselin Stoilov, and Andrzej Sobiesiak
Univ of Windsor

ABSTRACT

This paper describes the application of the Fourier Amplitude Sensitivity Test (FAST) method [1] to investigate the effect of uncertainty in design parameters on the thermal system performance of vehicle underbody components. The results from this study will pinpoint the design parameters which offer the greatest opportunity for improvement of thermal system performance and reliability. In turn, this method can save engineering time and resources.

An analytical model was developed for a vehicle underbody system consisting of a muffler, heat shield, and spare tire tub. The output from this model was defined as the temperature of the spare tire tub. The majority of the input parameters in this model deviate from their nominal values due to environmental factors, wear and ageing, and/or variation in the manufacturing process. Using MATLAB software package, the model was simulated with input parameters which were simultaneously and sinusoidally varied at distinct frequencies over their respective uncertainty ranges.

Finally, the Fourier transform was applied to the output of the model to convert the response into the frequency domain to allow the amplitude of each of the distinct frequencies to be recognized. The amplitude of each frequency was used as an indication of the effect of the corresponding parameter's variation on the temperature of the spare tire tub. Reducing the amount of variation in the most influential parameters and/or reducing the system sensitivity to these parameters will have the greatest improvement on the overall thermal performance of the system.

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INTRODUCTION

Underbody components are exposed to elevated temperatures due to their proximity to the exhaust system. Consequently, these components are designed to withstand high temperatures. However, the thermal performance of these components may vary based on environmental conditions, wear and ageing, and/or variation in the manufacturing process. For example, the emissivity of the muffler surface can increase drastically over time due to oxidation. As the emissivity of the muffler increases, the muffler will radiate a greater amount of heat to components which are within its radiation view path. Thus, the wear and ageing of the muffler will deteriorate the thermal performance of the surrounding components.

To ensure that the underbody components are designed robustly, it is important to understand the thermal performance's sensitivity to variation in input parameters. This study applies the Fourier Amplitude Sensitivity Test (FAST) to determine this sensitivity. The FAST method calculates the global sensitivity which is beneficial because the uncertainty is evaluated over the entire solution domain. This method is often used for environmental applications but can also be a powerful tool for automotive purposes, as shown by El-Sharkawy [1].

For this analysis, the FAST method was applied to a simple model consisting of a muffler, heat shield, and spare tire tub. The intent of this study was to determine the sensitivity of the spare tire tub temperature to variation in the model input parameters. Based on the results from this study, methods may be implemented to reduce the sensitivity of the spare tire tub temperature to variation in the most influential input parameters. Thus, the greatest improvement to the underbody thermal system performance may be realized.

In future work, this method can be applied to other vehicle systems to determine the effect of uncertainty in design parameters on critical vehicle performance targets.

METHODS

Fourier Amplitude Sensitivity Test (FAST)

FAST is a technique to conduct global sensitivity analysis. Global sensitivity analysis allows for sensitivity to be examined over the complete solution domain rather than a local approximation around the nominal values [1]. The FAST method calculates the partial variance of the input parameters so that the most influential parameters may be identified.

The fundamentals of the FAST method are described by El-Sharkawy [1]. The associated equations are given below:

The variance is calculated by:

$$\sigma_f^2 = \langle f^2 \rangle - \langle f \rangle^2 \quad (1)$$

Where f is calculated at a number of points within the uncertainty range of the input parameter.

The equation for the average, $\langle f \rangle$, is given by:

$$\langle f \rangle = \int \dots \int f(p_1, p_2, \dots, p_m) P(p_1, p_2, \dots, p_m) dp_1 dp_2 \dots dp_m \quad (2)$$

Where p is a parameter with a probability density of P .

Transforming this multiple integral into a one-dimensional integral can be accomplished using the transformation below:

$$p_l = G_l[\sin(\omega_l s)], \dots, l = 1, 2, \dots, n \quad (3)$$

$$\sum_{l=1}^n \gamma \omega_l = 0 \quad (4)$$

Where γ is an integer.

Variance of the parameters is calculated using the equation:

$$\sigma_{\omega_l}^2 = \frac{1}{2} \sum_{p=1}^{\infty} (a_{p\omega_l}^2 + b_{p\omega_l}^2) \quad (5)$$

Finally, the partial variance can be found by:

$$S = \frac{\frac{1}{2} \sum_{p=1}^{\infty} (a_{p\omega_l}^2 + b_{p\omega_l}^2)}{\sigma^2}$$

$a_{p\omega_l}$, $b_{p\omega_l}$: Fourier series coefficients

The uncertainty in the model is calculated as the following:

$$\frac{\sigma_f}{\langle f \rangle} * 100 \quad (6)$$

Development of Analytical Model

To apply the FAST method to an underbody component, an analytical model had to be established. The model created for this study considered a muffler with elliptical cross-section, a heat shield, and a spare tire tub which was approximated as a flat plate. The spare tire tub is exposed to radiation from the heat shield and convection due to underbody airflow. A simple schematic which depicts the modes of heat transfer between these components is shown in Figure 1.

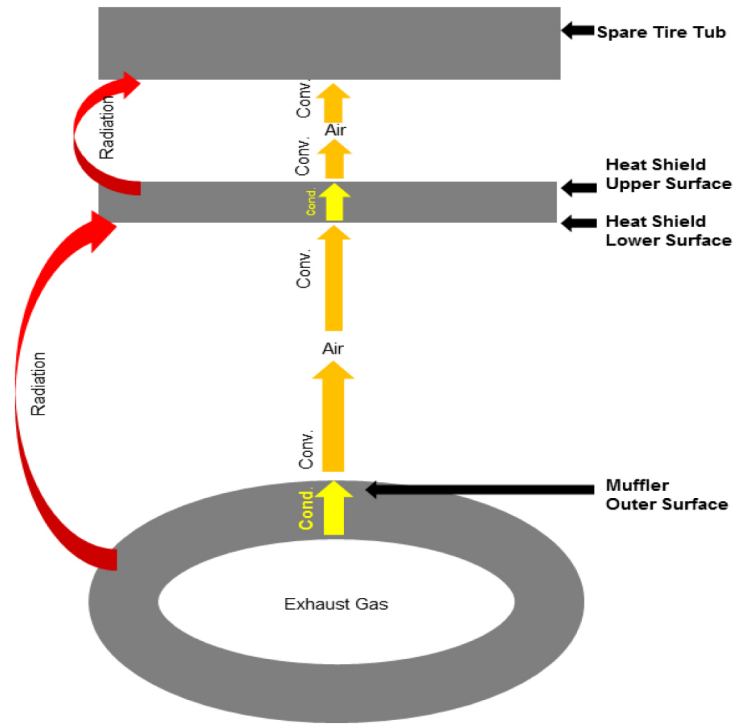


Figure 1. Cross-Section of Muffler, Heat Shield, and Spare Tire Tub. The transfer of heat through conduction, convection, and radiation are depicted between the components.

An energy balance equation was established for each surface shown in Figure 1. First, The energy balance equation for the muffler surface was developed, considering the convection heat transfer from the underbody air flow and conduction heat transfer through the muffler wall as shown in Equation 7:

$$m_m c_m \frac{dT_{mo}}{dt} = h_1 A_{mo} (T_a - T_{mo}) + \frac{2\pi k_m L_m (T_{mi} - T_{mo})}{\ln \frac{r_{mo}}{r_{mi}}} \quad (7)$$

m_m : mass of the muffler

c_m : specific heat capacity of the muffler

k_m : thermal conductivity of the muffler

T_a : temperature of the underbody airflow

T_{mi} : temperature of the muffler inner surface

T_{mo} : temperature of the muffler outer surface

h_1 : heat transfer coefficient between the underbody airflow and the muffler outer surface

L_m : length of the muffler

A_{mo} : surface area of the muffler outer surface

r_{mi} : inner radius of the muffler

r_{mo} : outer radius of the muffler