

Development of a Transient Thermal Analysis Model for Engine Mounts

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ABSTRACT

Engine mount is one of the temperature sensitive components in the vehicle under-hood. Due to increasing requirements for improved fuel economy, the under-hood thermal management has become very challenging in recent years. In order to study the effects of material thermal degradation on engine mount performance and durability; it is required to estimate the temperature of engine mount rubber during various driving conditions. The effect of temperature on physical properties of natural rubber can then be evaluated and the life of engine mount can be estimated.

In this paper, a bench test is conducted where the engine mount is exposed to a step change in the environment around it, and the temperature of the rubber section is recorded at several points till a steady state temperature is reached. A time response curve is generated, from which a time constant is determined. Based on the time constant, an engine mount thermal model is built using a series of first order system response curves. The developed model is compared against measured temperatures from actual vehicle test data. Modeling approach and results discussed in this paper provide guidance for predicting temperature distribution inside the engine mount rubber material under various driving conditions for future vehicle programs to improve the component robustness and durability.

CITATION: El-Sharkawy, A. and Uddin, A., "Development of a Transient Thermal Analysis Model for Engine Mounts," *SAE Int. J. Mater. Manf.* 9(2):2016, doi:10.4271/2016-01-0192.

INTRODUCTION

Thermal analysis and vehicle testing are usually conducted to determine the effect of time and temperature on material mechanical properties. A component life can be predicted if the component temperature history and vehicle duty cycle are available. Therefore, estimation or measurement of component temperature is critical for this process. Assuming steady state driving conditions may not capture transient component temperatures. For rubber materials with low thermal conductivity such as engine mounts, there will be a temperature gradient between the surface which is exposed to heat and the rest of the component. In this paper, the temperature difference between different locations inside the rubber material is investigated through application of thermal analysis models and by conducting bench test where actual measurements are made inside the rubber material.

The decay rate or thermal degradation can be estimated by using Arrhenius equation [1,2,3]. Therefore, the expected component life for a given driving cycle is directly affected by the component temperature.

To evaluate component temperature, vehicles are usually tested under various test scenarios designed to predict the component temperature under severe and under typical driving conditions. Accurate temperature measurements are therefore important to the control, performance, and normal operation of vehicle systems and

components. The effect of temperature on rubber tensile strength, for example, is illustrated in Figure 1. The data shown in Figure 1 was gathered by ageing rubber samples for several time durations at various temperatures. The tensile strength for rubber samples was subsequently measured. The results are expressed as normalized strength relative to initial tensile strength. Test data shows that a fifty percent reduction in tensile strength required a total exposure time of about 640 hours at a temperature of 94°C, 210 hours at a temperature of 105°C and only 70 hours at a temperature of 115°C. In all test data, all samples were allowed to reach uniform steady state temperature.

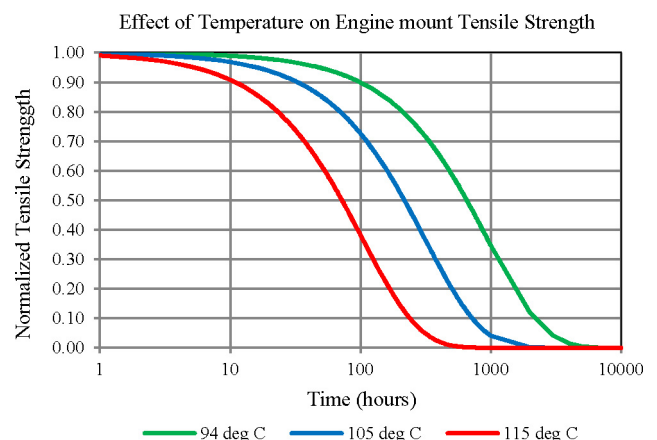


Figure 1. Effect of temperature on engine mount tensile strength

Therefore, component life can be estimated if the component temperatures is determined during driving conditions which represent a given customer duty cycle. Vehicle tests are therefore designed to capture the component temperature profile under various driving conditions. However, it is usually too costly to set up vehicles and run repetitive tests. In this paper an approach is presented where benefit can be made of previous vehicle test data in order to estimate component temperatures under new test conditions such as higher ambient temperature or different exhaust gas temperatures which may be caused by a change in engine calibration for example. Though this approach will help to reduce the number vehicle tests, a final validation test is still required. The approach adopted in this study is based on estimation of the time constant for the component based on vehicle level test data. The time constant can be estimated from the temperature response curve when a step change in the environment is introduced. The step change can represent a change in under-hood ambient temperature or exhaust surface temperature, or a combination of both.

The time constant depends on the material properties and heat transfer coefficient around the component. Therefore, it can be applied to predict component temperatures under any type of change in the forcing functions.

TEMPERATURE RESPONSE FOR A RUBBER EMBEDDED THERMOCOUPLE

Uncertainties in component temperature measurements and estimates have been investigated by the author in earlier publications [4,5,6,7]. Most significant issues arise when the thermocouple is not embedded in the component material and is exposed the radiation from the exhaust surface for example. This issue can be avoided by making sure that the thermocouples are measuring the rubber material and is not affected by the external radiation. The uncertainties in embedded thermocouple measurements depend on the location inside the engine mount for example. Variation in the measurement location will affect the thermocouple response time and magnitude. It is therefore recommended that the measurement location should be about 2-3 mm from the outer surface when radiation effect is being evaluated. This guarantees a quick response while avoiding effects of radiation on the heat absorbed by thermocouple junction.

To determine the component internal temperature at various locations within the rubber material of an engine mount, we are applying the thermal response model for an embedded thermocouple [4]. The thermal energy balance for an embedded thermocouple is given by the following set of equations:

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c_p} \frac{\partial^2 T}{\partial x^2} = \alpha \frac{\partial^2 T}{\partial x^2} \quad (1)$$

Subject to the following conditions:

$$\text{at } x = 0 \quad -k \frac{dT}{dx} \Big|_{x=0} = hA(T - T_{air}) \quad (2)$$

$$\text{at } x = l \quad -k \frac{dT}{dx} \Big|_{x=l} = -k_c \frac{dT_c}{dx} \Big|_{x=l} \quad (3)$$

$$\text{and} \quad T(x, t = 0) = T_0 \quad (4)$$

where l is the distance from surface to internal thermocouple location, T_c is thermocouple temperature, and k_c is thermocouple thermal conductivity. A schematic diagram of the embedded thermocouple in the rubber material is shown in Figure 2.

Using dimensionless parameters ξ and θ where:

$$\xi = \frac{x}{l} \quad \text{and} \quad \theta = \frac{T - T_1}{T_0 - T_1} \quad (5)$$

The time and heat transfer coefficient may be written as:

Dimensionless time, Fourier number (F_0) where

$$F_0 = \frac{\alpha^2 t}{l^2} \quad (6)$$

and the dimensionless coefficient, Biot number (Bi) where

$$Bi = \frac{hl}{k} = \frac{l/k}{1/h} \quad (7)$$

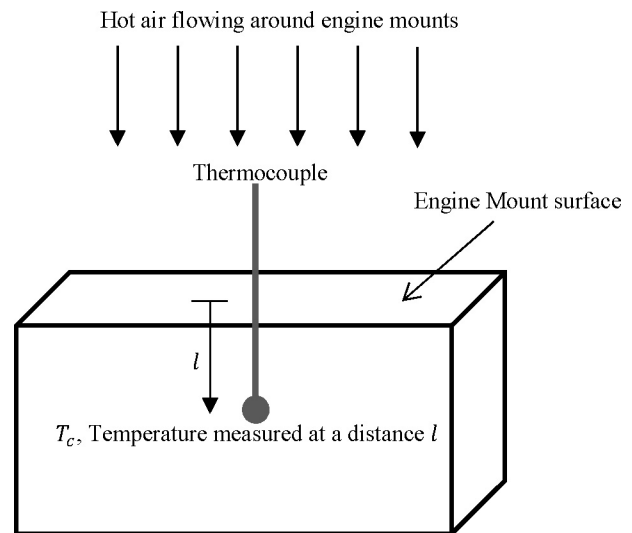


Figure 2. Thermocouple embedded in a rubber engine mount section

The parameters F_0 and Bi are important measures of how the component will respond to thermal changes. The Fourier number, F_0 , is a dimensionless measure of time. From equation (6), components with high diffusivity and smaller dimension will respond faster to temperature changes. The Biot number, Bi , is a measure of the ratio of thermal resistance of the body, l/k , and thermal resistance of the surface film $1/h$. Therefore, the response of components will now be is controlled by the surface resistance.

To determine the response of embedded thermocouple, we consider the case where a step change in the surface temperature from initial temperature T_0 to a new temperature T_1 is applied. The response of thermocouple will depend on its location inside the measured medium and also on the medium thermal properties and size. The response of a thermocouple to this change is similar to the solution presented by Rabin and Rittle [8] in the following form:

$$\frac{T - T_1}{T_0 - T_1} = \exp \left[-B \left(\frac{at}{l^2} \right)^n \right] \quad (8)$$

The coefficients B and n are determined based on experimental data and are related to thermal diffusivities of the thermocouple junction material and the medium being measured. For copper wire of the thermocouple and for a rubber medium, the diffusivities are found to be $1.1 \times 10^{-4} \text{ m}^2/\text{s}$ and $9.8 \times 10^{-8} \text{ m}^2/\text{s}$, and the corresponding values for B and n are approximately 1.833 and 0.45. In equation (8), it is assumed that there is no thermal resistance between the material being measured and the thermocouple junction.

The data are shown in Figure 3 for thermocouple response when the junction is located at different distances from the front of a rubber component. At 1 mm distance, the thermocouple temperature reaches T_1 without any significant time lag. At locations greater than 2-3 mm, the time lag becomes more significant. At these locations, the thermocouple measurement should not be considered as a surface measurement, but rather as an internal measurement.

Based on the results from the above chart, it is clear that there is a significant temperature gradient inside the rubber component such as the engine mount. The magnitude of the temperature gradient depends on the test duration, rubber thickness, its thermal conductivity and the magnitude of change in the forcing function (such as change in ambient temperature or exhaust surface temperature).

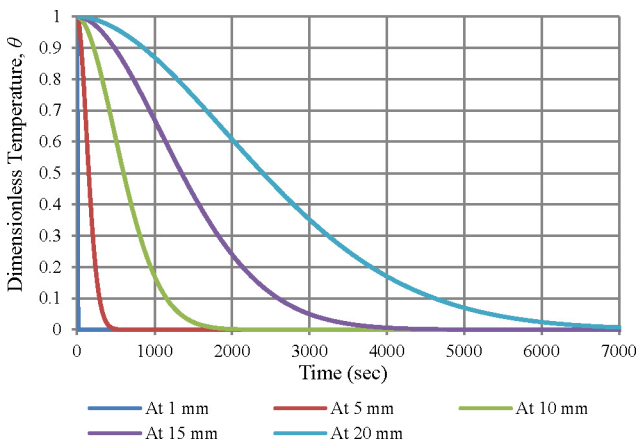


Figure 3. Effect of thermocouple location on thermocouple response

APPLICATION OF TIME CONSTANT FOR ESTIMATION OF COMPONENT TEMPERATURES

Based on results from figure 3, it is evident that significant time lags may exist inside the material thickness. Therefore, the time constant will vary depending on the measurement location. Therefore, an estimate of the time constant is required. For evaluation of the time constant, that general energy balance for a transient system can be written as

$$m_c c_p \frac{\partial T_c}{\partial t} = hA(T_{air} - T_c) + \sigma \epsilon FA(T_{exh}^4 - T_c^4) - k_c A \frac{\partial T_c}{\partial r} \quad (9)$$

where m_c is the component mass and c_p is the heat capacity, h is the convection heat transfer coefficient, A is the surface area, T_c is the component temperature, σ is the Stefan-Boltzmann constant, ϵ is the emissivity, and k_c is the material thermal conductivity [9].

For a system with limited conduction resistance, the equation can be simplified to the following:

$$m_c c_p \frac{dT_c}{dt} = hA(T_{air} - T_c) + \sigma \epsilon FA(T_{exh}^4 - T_c^4) \quad (10)$$

In absence of radiation, the heat transfer is controlled by convection and the equation can be simplified to

$$m_c c_p \frac{dT_c}{dt} = hA(T_{air} - T_c) \quad (11)$$

The transient equation can be reduced to:

$$\frac{dT_c}{dt} = \left(\frac{hA}{m_c c_p} \right) (T_{air} - T_c) \quad (12)$$

$$\text{or } \left(\frac{m_c c_p}{hA} \right) \frac{dT_c}{dt} = (T_{air} - T_c) \quad (13)$$

Time constant of the system can be denoted by

$$\tau = \frac{m_c c_p}{hA} \quad (14)$$

Thus the system equation can be written as:

$$\tau \frac{dT_c}{dt} = (T_{air} - T_c) \quad (15)$$

At steady-state condition: $T_c = T_{air}$