A Channel Model for Wireless Sensor Networks in Gas Turbine Engines

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Abstract—A narrowband channel model (2.4 GHz to 2.5 GHz) for wireless sensors deployed over the external surfaces of a gas turbine engine is reported. The model is empirical and based on a series of transmission loss measurements over the surface of a gas turbine engine.

I. INTRODUCTION

Wireless sensing offers a potential step change in gas turbine engine testing by alleviating a number of significant disadvantages associated with the wired solution currently used. These disadvantages include lengthy, complicated and expensive wiring harnesses, complex set up processes and instrumentation, designing flexibility, and inefficient data gathering. Currently the aerospace industry is assessing wireless sensor kits for test measurements. In this paper a wireless channel model derived from a set of channel measurements is presented in support of a wider project to assess the potential of wireless sensor networks for the condition monitoring of gas turbine engines.

II. METHODOLOGY

A series of frequency response measurements between pairs of points distributed on a grid over the cylindrical surface of an unenergised Gnome gas turbine engine have been undertaken. The measurements, covering the range 2.4 GHz to 2.5 GHz, have been made without (measurement set 1), and with (measurement set 2) an engine cowling. The corresponding measurement databases form the basis of an empirical transmission gain model.

The measurements were made between a pair of rectaxial antennas [1] using an Agilent N5230A network analyser. Figure 1 (a), shows one of the antennas and Figure 1 (b) shows its measured return loss (S_{11}).

Each antenna was connected to the network analyser using 10 m of high-quality, low-loss, RF cable.

The antennas were mounted on a PVC rod to minimise the effect of scattering from the metallic antenna positioners. The

Fig. 1. (a) Rectaxial antenna and (b) measured return loss (S_{11}).

antenna positioners were shrouded with RF absorber, Figure 2 (a).

The Gnome engine was mounted on a tubulous steel framework, Figure 2 (b). The framework was shrouded with RF absorber to minimise unwanted reflections. For both measurement set 1 and 2, the span of the network analyser was set to 100 MHz with a centre frequency of 2.45 GHz. The number of samples within the span (2.4 GHz–2.5 GHz) was set to 6401. The frequency sampling interval was therefore 15.62 kHz.

The Gnome engine is approximately cylindrical, Figure 2 (b). The length of the engine is 78 cm and its mean radius is 18 cm.

A. Measurement Set 1

These measurements were undertaken in the Gnome Test Laboratory at Rolls-Royce premises in Derby, UK. The engine for these measurements had no cowling. The geometry of the measurements is illustrated schematically, in Figure 3. Six potential measurement points were distributed evenly around the circumference of the engine in five planes distributed along the length of the engine and perpendicular to the engine axis. The separation between adjacent planes was 28 cm, 24 cm, 6 cm and 20 cm. This is illustrated schematically in Figure 3.

There were, therefore, 30 potential measurement points in

Fig. 2. (a) Antenna positioners and (b) Gnome engine.

Fig. 3. Schematic diagram of engine measurement points (set 1).

total. Since measurement time was limited and since measurements between all pairs of potential points includes redundant geometries one pair of points on each plane were omitted from the measurement process. These are represented by black points in Figure 3. The total number of planned measurements between all pair of points was thus 190. The actual number of measurements made was 136; the balance of 54 measurements being cut due to the constrained time available in the Gnome engine laboratory. The residual redundancy in measurement geometries, however, means that all geometries are satisfactorily represented in the measurement database.

B. Measurement Set 2

These measurements were undertaken in the Wireless Communications Laboratory at the University of Strathclyde. The Gnome engine used was identical in type but a different instance of that used for measurement set 1. The surface detail of the two engines was similar but not identical. The engine for these measurements were in the presence of an engine cowling manufactured by SCITEK Consultants Ltd. from stainless steel mesh, Figure 4.

Fig. 4. Gnome engine with cowling.

Six potential measurement points were distributed evenly around the circumference of the engine in three planes distributed along the length of the engine and perpendicular to the engine axis. The separation between adjacent planes was 25 cm and 26 cm. This is illustrated schematically in Figure 5. One pair of points in each plane (black in Figure 5) was again neglected. The total number of planned measurements was therefore 66. The number of measurements actually made was 65.

Fig. 5. Schematic diagram of engine measurement points (set 2).

III. TRANSMISSION GAIN MODEL

A transmission gain model has been derived from the measurement database. In order to make the model generic, such that it can be applied to engines of arbitrary size, the model is parameterised in terms of path length, s , and path curvature, κ . Figure 6 shows a schematic diagram of the path geometry.

Fig. 6. Schematic diagram of path geometry.

The path length of each measurement is that of a curved arc connecting transmitter (P_1) and receiver (P_2). The arc length s is given by:

$$s = \sqrt{(r\phi)^2 + l^2} \quad (1)$$

where r is engine radius, ϕ is angular separation between P_1 and P_2 projected onto a plane perpendicular to the engine access and l is the linear separation of the planes perpendicular to the engine axis containing P_1 and P_2 .

The path curvature, the reciprocal of path radius curvature, is given by:

$$\kappa = \frac{r}{r^2 + \left(\frac{l}{\phi}\right)^2} \quad (2)$$

It is a fundamental assumption of the generic model that s and κ are sufficient to predict transmission loss and that the effect of path torsion on loss is small. It is also assumed that narrowband modelling of transmission loss is adequate for practical engineering purposes.

Analysis of the measurement database has been undertaken (using MatLab) and the best fit (MMSE) first-degree polynomial, $As + B\kappa + C\bar{G}_T + D = 0$, where $\bar{G}_T$ is mean transmission gain in dB (< 0), has been derived. The resulting best-fit surface for measurement sets 1 and 2 are shown in Figures 7 and 8 respectively.

Fig. 7. Measurement data (set 1) and best-fit first-degree surface.

Fig. 8. Measurement data (set 2) and best-fit first-degree surface.

Figures 9 and 10 show the projection of Figures 7 and 8, respectively, chosen to illustrate the influence of path length.

Fig. 9. Two dimensional projection of data (set 1) illustrating transmission gain versus path length.

Fig. 10. Two dimensional projection of data (set 2) illustrating transmission gain versus path length.

Table I shows the best-fit polynomial coefficients derived for each measurement set.

	Polynomial Coefficients			
	A	B	C	D
Measurement Set 1	-0.99986	0.00043	-0.01678	-0.30833
Measurement Set 2	-0.99983	-0.010042	-0.01532	0.02659

TABLE I
TRANSMISSION MODEL POLYNOMIAL COEFFICIENTS.

The error between the measured data and the first-degree model is:

$$\epsilon_{dB} = G_{Tmeasured} - G_{Tmodel} \quad (3)$$

This has been modelled in the same way as the original data, Figure 11. Figure 12 shows a projection of Figure 11 chosen to illustrate the influence of path length.

Fig. 11. Difference (ϵ) between measurement points and best-fit surface:(a) measurement set 1 (b) measurement set 2.

Fig. 12. Projection of data in Figures 11(a) and (b) illustrating dependence of ϵ on path length.

The 2-dimensional space spanned by s and κ is quantized in a 4 (s) by 3 (κ) grid and the histogram of ϵ within each 2-dimensional quantization interval is constructed. The mean and standard deviation of the histogram data are calculated. Figure 13 shows an example histogram and the normal distribution corresponding to the data's mean, μ , and standard deviation, σ . The dependence of μ and σ is again modelled on s and κ using a first-degree polynomial surface, Figures 14 and 15.

The random surface detail of the gas turbine engine means that path loss must be modelled statistically. The transmission gain model proposed therefore comprises a deterministic component, $\bar{G}_T(s, \kappa)$, and a random component $e(s, \kappa)$ where e is a Gaussian random variable with mean and standard deviation that depend on s and κ , i.e.:

$$G_T(s, \kappa) = \bar{G}_T(s, \kappa) + e[\mu(s, \kappa), \sigma(s, \kappa)] \quad (4)$$

Fig. 13. Histogram of error within a single s - κ quantization interval and corresponding normal distribution.

Fig. 16. Transmission gain model.

IV. CONCLUSION

A comprehensive set of narrowband transmission loss measurements for wireless sensor nodes deployed around the surface of a gas turbine engine have been reported. The measurements have been made in the ISM band using a pair of omni-directional rectaxial antennas. The measurements have been made both in the presence of, and in the absence of, an engine cowling.

A generic model with parameters arc length and path curvature has been derived. The model, which includes deterministic and random components, has been implemented in Simulink and is a part of a simulation platform including an interference [2] and a noise model.

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Fig. 14. (a) μ versus s , κ and (b) σ versus s , κ for measurement set 1

Fig. 15. (a) μ versus s , κ and (b) σ versus s , κ for measurement set 2