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Theoretical characterization of a gas path debris detection monitoring system based on electrostatic sensors and charge amplifiers

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ABSTRACT

The electrostatic detection of gas path debris has been proposed in literature as a tool to monitor mechanical component faults along the combustion gas path of turbo-machines. In this paper we discuss the general theoretical characterization of a debris detection monitoring system based on electrostatic sensors and charge amplifiers. We first provide the analytical expression of the time-varying charge induced by the moving debris on the sensor surface. After introducing a simplified electric model of the charge amplifier, we discuss the effects of the amplifier bandwidth on the shape of the output voltage signal. Theoretical results have been validated with experiments.

1. Introduction

To assess the operational health of aero-engines or gas-turbines, several condition monitoring systems has been investigated in literature to provide early warning of potential failures, such that preventive or predictive maintenance actions may be taken [1–11]. The condition monitoring of aero-engines or gas-turbines is a structured process including several measurement techniques providing signals that are used to detect changes in the machinery operation, which can be indicative of a developing fault. Among the different methods that concur to the condition monitoring of a turbine, the electrostatic detection of debris has been proposed in literature as a tool to identify component faults involving the combustion gas path [1,2,4,12–18].

The debris expelled with the exhaust gas is typically electrically charged with a charge level that depends on several factors, among which the debris material and its size, the type of the mechanical fault, the temperature and other physical properties of the gas [1,19]. On the other hand, as discussed in detail in this paper, the shape of the measured signal depends on the debris speed, on the distance of the debris trajectory from the sensing equipment, on the frequency response of the conditioning devices and on the probes and cables electrical properties. Moreover, the environmental electromagnetic noise can play an important role in limiting the minimum detectable charge level.

Referring to Fig. 1, in this paper we discuss the theoretical characterization of a debris detection system based on electrostatic sensors and charge amplifiers. This work aims at providing a reference framework for the design of measurement chains to monitor gas path debris, showing that the measurement result depends on the interaction between the debris charge, velocity and trajectory, the

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sensor size and the conditioner amplifier bandwidth. Differently from other approaches proposed in literature, based on heuristic models or electrostatic numerical Finite Element Analysis [1,4,13,14,17,18,20–22], the results presented in this paper were derived from the physics and the electrical modeling of the amplifier, proposing a theoretical link between the debris dynamics and the measured signal shapes.

The proposed analysis, that has been validated with experiments, has a general validity since the theoretical framework takes into account physical and electrical models holding for a wide range of operating applications, including turbines condition monitoring, flow measurement and atmospheric research [1,2,4,12–18,20–22].

A measurement set-up similar to that one shown in Fig. 1 has been recently analyzed by Zhenhua et al. [17], evaluating the spatial sensitivity of a charge detection electrode by fitting numerical calculations with the Finite Element Analysis. The general characterization discussed in our work is in agreement with the numerical and experimental results presented in [17].

2. Expression of the charge density induced on the sensor surface

Without loss of generality, we can provide a simplified (but reliable) expression of the charge density induced on the sensor surface by assuming the sensor plate as a limited portion of a infinite metallic plane. The experimental results confirmed the validity of this assumption when considering the typical geometrical dimensions of the exhaust conduits of gas turbo-machines.

Accordingly, referring to Fig. 2, we denote with h the distance of the charge from the plane, and with d the distance between any point of the metallic plane surface and the plane-projection of the charge. The electrostatic field produced by the charge can be easily calculated using the method of the image charges [23], whereas the charge surface density σ_s induced on the metallic plate can be calculated using the Gauss electrostatic theorem, i.e.:

$$\sigma_s(d,h) = \varepsilon_0\varepsilon_r E_s(d,h), \tag{1}$$

where E_s is the surface electrostatic field orthogonal to the plane. Omitting some calculations, we obtain

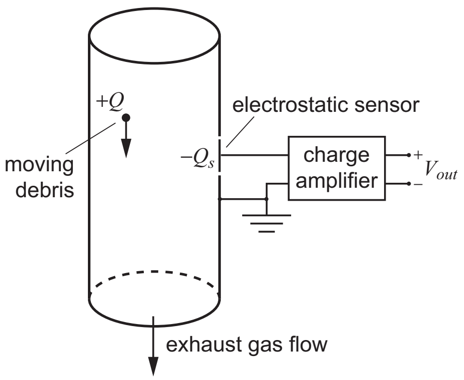

Fig. 1. A schematic representation of the measurement setup.

$$\sigma_s(d,h) = \frac{-Q\ h}{2\pi(d^2+h^2)^{3/2}}. \tag{2}$$

For a given debris distance h, the maximum of (2) is obtained for $d = 0$. A graphical representation of (2) is reported in Fig. 3, where the surface charge density has been normalized to the value of (2) for $d = 0\lambda, h = 1\lambda$, being the distances h, d expressed in an arbitrary unit of length λ.

As a result, the surface charge Q_s induced on the sensor plate can be obtained by integration, i.e., if S is the sensor area then

$$Q_s = \int_S \sigma_s(d,h)dS = \iint \sigma_s(d(x,y),h)dxdy. \tag{3}$$

At a first approximation, as it can be seen in Fig. 3, the surface charge density can be considered reasonably constant over circular regions with area $\pi\lambda^2$ if the distance h is greater than 6 times λ. As a result, if r is the sensor radius, in such a condition we have from (3) and (2)

$$Q_s \approx \frac{-Q\ h\ r^2}{2(d^2+h^2)^{3/2}}, \tag{4}$$

where the quantity d can be considered as the distance between the center of the sensor and the projection of the debris position on the sensor plane, as shown in Fig. 4. The time-dependency of the above result (due to the debris trajectory) can be made explicit as

$$Q_s(t) \approx \frac{-Q\ h(t)\ r^2}{2(d^2(t)+h^2(t))^{3/2}}. \tag{5}$$

The above expression can be used to estimate the output voltage signal of the monitoring system, taking into account the circuit model of the charge amplifier discussed in the next section.

3. Circuit model of the charge amplifier

At a first approximation a charge amplifier can be modeled with the circuit of Fig. 5. The impedance given by the parallel of C_p and R_p takes into account of the leakages and the capacitive coupling with the ground, introduced by the sensor and the connection cables. On the other hand, the feedback impedance given by the parallel of C_f and R_f set the nominal gain and the frequency response of the current integrator.

The circuit can be analyzed assuming for the operational amplifier the typical single-pole response

$$A(\omega) = \frac{A_0}{1+j\frac{\omega}{\omega_H}}. \tag{6}$$

The input current is given by the time-variation of the induced charge on the sensor, i.e., $I_s = \frac{dQ_s}{dt}$. Accordingly, the output voltage in Fig. 1 can be expressed in the frequency domain, recalling that $I_s(\omega) = j\omega Q_s(\omega)$, and obtaining

$$\begin{aligned} V_{out}(\omega) &= \frac{-A(\omega)R_pR_f\ I_s(\omega)}{R_f+(A(\omega)+1)R_p+j\omega R_pR_f(C_p+(A(\omega)+1)C_f))} \\ &= \frac{-j\omega A(\omega)R_pR_f\ Q_s(\omega)}{R_f+(A(\omega)+1)R_p+j\omega R_pR_f(C_p+(A(\omega)+1)C_f))}. \end{aligned} \tag{7}$$