

Stability Analysis of a Disc Brake with Piezoelectric Self-Sensing Technique

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Abstract

Piezoelectric self-sensing allows to measure frequency response functions of dynamical systems with one single piezoelectric element. This piezoceramics is used as actuator and sensor simultaneously. In this study, a model-based piezoelectric self-sensing technique is presented to obtain potential squealing frequencies of an automotive disc brake.

The frequency-response function of the brake system is obtained during operation by measuring the current flowing through the piezoelectric element while the piezoelectric element is driven by a harmonic voltage signal with constant amplitude. The current flow is composed of the part which is required to drive the piezoelectric element as an actuator and a second part which is the sensor signal that is proportional to the vibration amplitude of the attached mechanical system. Typically the first part is dominant and the influence of the mechanical system is marginal.

With an idealized mathematical model of the piezoelectric element, the admittance can be calculated and the actuator current eliminated from the measured signal. This software-based solution does not require any additional electrical circuits or precise tuning during the measurements.

Potential squealing frequencies which agree with the eigenfrequencies of the brake model can be determined in the recalculated signal. When the brake is heated up, one of these resonances stands out in the measurements, even if the brake does not squeal at that moment. This frequency is the most critical one and it is a very good indicator for potential squealing frequencies of the brake. The pro-

posed technique is therefore helpful especially during the development of new brake systems, where the stability of various brake prototypes must be determined quickly so that the necessary modifications can be carried out.

INTRODUCTION

Piezoceramics are widely used as actuators and sensors in technical systems. They offer very precise motion and high dynamics. Typically the piezoelectric elements are either used as an actuator to generate a force or deformation of the mechanical structure or as a sensor to measure the deformation. Sensor/actuator pairs are broadly used for vibration control, where the output of the sensor is fed back to the actuator. Measuring frequency response functions is also typically performed with actuators and sensors, where the actuators are driven by harmonic input signals and the sensors measure the vibration amplitudes of the mechanical system. Non destructive condition monitoring is another technique relying on the measurement of frequency responses [1]. In this case the modal parameters of the system under investigation are derived from the frequency response, and significant changes in these parameters are linked to certain failures of the system. Process monitoring is another technique that improves the quality and lifetime by measuring the system's response [2].

In most of these cases it is desirable to reduce the number of actuators and sensors. The properties of the mechanical structure are less modified if the number of piezoelectric elements can be reduced. Also the complexity and the required space are lower. Especially for systems that are very sensitive to small changes in geometry, mass and stiffness it is essential to reduce the number of transducers to a minimum. The squealing of disc brake is one phenomenon

known to be very sensitive to system parameters' variations [3]. Therefore, a brake equipped with piezoelectric transducers might show a totally different squealing behavior compared to the original brake. In this case it is mandatory to reduce the number of transducers to a minimum.

A reduction can be achieved if one transducer is used as actuator and sensor simultaneously, eliminating the need of additional sensors. Such techniques are called self-sensing. The input voltage at the piezoelectric element is controlled, and the current is measured. However, the current signal does not only contain the sensor signal which is generated by the mechanical vibrations, but also the current that is required to operate the transducer as an actuator, which in most cases is several times larger. It is therefore difficult to distinguish both signals [4].

Bridge circuits are typically used to separate the control voltage and the sensing signal [5, 6]. These balanced bridge circuits use a dummy sensor to compensate the actuator effect. In this case it is possible to compensate the variations of the piezoelectric element due to environmental changes like temperature. But still these circuits must be precisely tuned, otherwise stability problems arise.

Self-sensing comes with additional advantages especially for control applications. As the actuator and the sensor are truly collocated (because they are actually the same piezoelectric element), this results in guaranteed unconditional stability of certain local feedback structures like direct velocity feedback [7]. Piezoelectric shunt damping is another technique that is related to self-sensing [8, 9]. In this case, the transducer is shunted to an electrical circuit, which is designed to dissipate energy and subsequently increase the damping of the mechanical structure. This technique has also been successfully adopted for the suppression of brake squeal [10].

In this study, a model-based self-sensing technique is presented. The actuator signal is not eliminated in hardware, but it is done in software with a mathematical model of the piezoelectric element. This can be either done online during the measurement or in a post-processing process of the data. This approach has the advantage that no stability problems occur, and the properties of the piezo element for the postprocessing can be varied and optimized afterwards, improving the result [11]. The mechanical structure under investigation is an automotive disc brake. A similar technique was proposed in [12], albeit with the classical actuator/sensor pair. In this paper it is shown that the self-sensing technique can be used to detect potential squealing frequencies of the brake, even if the brake does not squeal during the measurements.

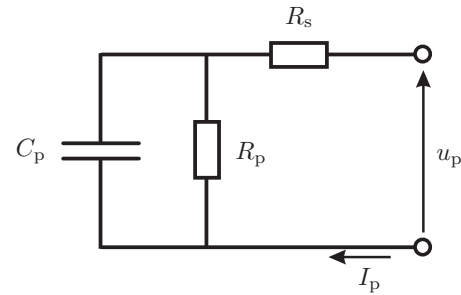


Figure 1: Electrical circuit model for piezoelectric element.

PIEZOELECTRIC MODEL

A common electrical representation of a piezoelectric element is given in Fig. 1. In this static model the piezo element is represented by its inherited capacitance C_p , by the insulation leakage resistance R_p and a serial resistance R_s . The capacitance of a piezoceramics is given by $C_p = \epsilon A/l$, with the electrical permittivity ϵ , the area A of and the distance l between the electrodes. The parallel resistance R_p is rather high, yet not infinity. The serial resistance R_s is small in the range of a few Ω and includes the losses in the connecting wires.

When the piezo element is attached to a vibrating mechanical system, the piezoelectric effect transforms kinetic energy into electrical energy. For small oscillations which are considered in the following, the dependency is linear and can be described by the force factor α of the piezoceramics,

$$Q_{p,sens} = \alpha x, \quad \text{or} \quad F_p = -\alpha u_p. \quad (1)$$

In sensor operation the generated charge $Q_{p,sens}$ (and therefore also the voltage u_p) is proportional to the deformation x of the mechanical structure. For an actuator the force F_p is proportional to the applied voltage u_p , with the same proportionality factor α .

ONE DEGREE OF FREEDOM OSCILLATOR

If the classical one degree of freedom oscillator is examined as the mechanical host structure, the combined electromechanical system can be represented by the mechanical replacement model given in Fig. 2. The mechanical structure is represented by its parameters stiffness c , damping d and mass m with the amplitude x as the degree of freedom. The lever α links the mechanical and electrical properties. The electrical model of the piezoelectric element from Fig. 1 is equivalent to the mechanical representation with spring $1/C_p$ and damping elements R_s, R_p . The deformation of the free end equals the electrical charge Q_p at the electrodes and the external force is the electrical voltage u_p .

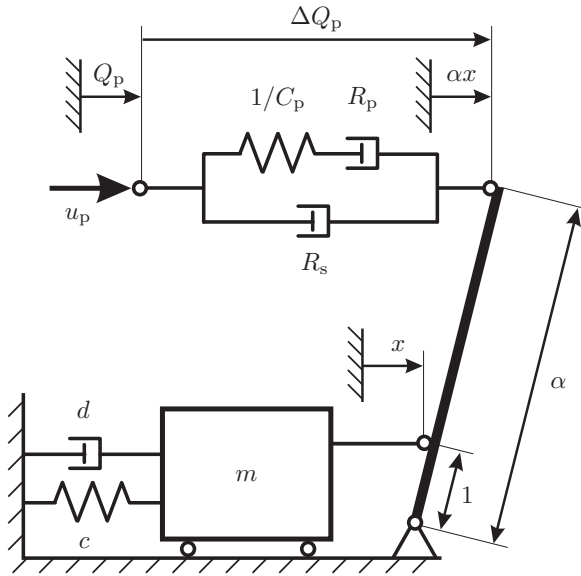


Figure 2: Mechanical replacement model for 1 DOF oscillator with piezoelectric element.

When the piezoelectric element is used as an actuator, it is driven by a voltage or current input and generates a force and deformation of the mechanical system. When the sensor effect is used, the mechanical deformation is obtained by measuring the voltage u_p or charge Q_p at the electrodes.

In the piezoelectric self-sensing technique, both effects are utilized simultaneously. The piezoelectric element is driven by a harmonic voltage u_p , and at the same time the current I_p , which is the time derivative of the charge Q_p , is measured. However, as it is apparent from the mechanical replacement model, it is not possible to directly measure the mechanical deformation x . The charge Q_p , which is the deformation of the free end in Fig. 2 can be measured, but this signal is not proportional to mechanical deformation $\alpha^2 x$ because of the admittance Y of the piezoelectric element. This admittance causes a deformation of the piezoelectric subsystem in Fig. 2, in the following termed ΔQ_p . Especially for low electromechanical coupling of the system (low force factor α), ΔQ_p might be dominating in the measurements and therefore must be eliminated.

The idea of the proposed model-based self-sensing technique is to calculate an estimation for the deformation ΔQ_p , which can subsequently be subtracted from the measured charge Q_p , so that the mechanical deformation $\alpha^2 x$ can be obtained. The calculation of ΔQ_p is performed with the idealized piezoelectric model shown in Fig. 1. To obtain good results it is necessary to have precise estimations of the piezoelectric parameters C_p , R_s , R_p . In the case of perfect estimations the recalculated signal is exactly proportional to the mechanical deformation of the structure.

After some basic mathematics the differential equation for the current $\Delta I_p = \Delta \dot{Q}_p$ is obtained [11],

$$(R_p + R_s) \Delta I_p(t) + C_p R_p R_s \Delta \dot{I}_p(t) = u_p(t) + C_p R_p \dot{u}_p. \quad (2)$$

In case of harmonic excitation, the exponential ansatz $u_p(t) = \hat{u}_p e^{j\Omega t}$ with complex amplitude $\hat{u}_p$ can be used to solve the equation. Divided into real and imaginary part, the admittance reads

$$Y = \frac{\Delta \hat{I}_p}{\hat{u}_p} = \frac{R_p + R_s + \Omega^2 C_p^2 R_p^2 R_s}{(R_p + R_s)^2 + (\Omega C_p R_p R_s)^2} + j \frac{\Omega C_p R_p^2}{(R_p + R_s)^2 + (\Omega C_p R_p R_s)^2}. \quad (3)$$

Because of the resistive and capacitive elements, the admittance is frequency-depending and complex. The signal for $\Delta Q_p(t)$ is therefore generally not in phase with the excitation $u_p(t)$ and the mechanical deformation $x(t)$. Fig. 3 shows a typical plot for amplitude $|Y| = \sqrt{\text{Re}\{Y\}^2 + \text{Im}\{Y\}^2}$ and phase $\varphi = \arctan(\text{Im}\{Y\}/\text{Re}\{Y\})$. The result is very similar to the one of an ideal capacitance C_p ($R_p \rightarrow \infty$, $R_s = 0$). The amplitude is approximately $|Y| \approx \Omega C_p$ with a phase of nearly $+90^\circ$.

In the following, the mechanical oscillator from Fig. 2 is studied as an theoretical example. The mechanical admittance $Y_{\text{mech}} = \hat{x}/\hat{F}$ of the oscillator reads

$$Y_{\text{mech}} = \frac{\hat{x}}{\hat{F}} = \frac{1}{d + j(m\Omega - \frac{c}{\Omega})}. \quad (4)$$

The lever of length α has the effect that the electrical properties are multiplied by a factor α when transformed into the mechanical subsystem. The same applies for the reverse transformation from mechanical into electrical subsystem. This means that the force that is acting on the mechanical system reads $F = \alpha u_p$ while the amplitude αx is included in the measured signal. Because of the two-time conversion, the proportionality factor α appears squared in the measured signal. The overall current I_p that is measured at the piezoelectric element reads

$$\hat{I}_p = \Delta \hat{I}_p + \alpha \hat{x}. \quad (5)$$

Both terms on the right side of the equation can be replaced by Eqs. 3 and 4:

$$\hat{I}_p = \left(Y + \alpha^2 \frac{1}{d + j(m\Omega - \frac{c}{\Omega})} \right) \hat{u}_p. \quad (6)$$

For the charge Q_p it follows

$$\hat{Q}_p = -j \frac{1}{\Omega} \hat{I}_p. \quad (7)$$