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Model based defect detection for free stator of ultrasonic motor

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Abstract: In this paper, measurements of admittance magnitude and phase are used to identify the complex values of equivalent circuit model for free stator of an ultrasonic motor. The model is used to evaluate the changes in the admittance and relative changes in the values of equivalent circuit elements. This method identifies the damages and categorizes them. The validity of the method is verified by using free stator measurements of defect free stators of a recently developed multilayer piezoelectric motor.

Key words: Ultrasonic motor, defect detection, equivalent circuit, NDE, NDT

A. Introduction

Structural health monitoring is a subject that has received considerable attention and remains an active research area. Traditional non-destructive testing and evaluation (NDT and NDE) techniques include ultrasonic technology [1], acoustic emission [2], magnetic field analysis [3], penetrate testing [4], eddy current techniques [5], X-ray analysis [6], impact-echo testing [7], global structural response analysis [8] and imaging and usage of wavelet [9]. These methods propose many different algorithms for identifying and localizing the damage. Most of the available NDE/NDT methods are not model based [10]. Almost all of the non-model based techniques require that the vicinity of the damage is known in advance and the portion of the structure being inspected is readily accessible. Furthermore, the non-model based methods (experimental methods) can provide only local information and no indication of the structural strength at a system. Piezoelectric material has been widely used for impedance-based health monitoring and defect detection in composites and other structures and many literatures have reported these applications and different methods are developed on these bases [11]-[12]. But there have been relatively few research efforts in studying the defect detection in piezoelectric composite itself by monitoring the changes of impedance based on the electrical model of the structure. Here we introduce a model based method for evaluating the defects in the stator of ultrasonic rotary piezoelectric motor. This method can be used for assessing the defects based on the changes in the material parameters. The method is based on the equivalent circuit model in transversal mode presented in our earlier published works [14]-[15]. As the case study, the approach is applied in two scenarios to a miniature rotary piezoelectric motor. The model can be used for evaluating the defects in each phase of the free stator. The material parameter identification method which is presented in our previous work [14] is used for identifying the material parameters.

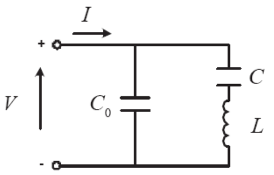

Fig.1. The proposed complex circuit model by Mojallali *et al.* [29]. The values of the circuit constants are complex

B. Model

Figure 1 shows the derived equivalent circuit model for each phase of stator of an ultrasonic piezoelectric motor [14]. The circuit elements, C_0, L and C in this model, are complex. In this circuit, C_0 forms the dielectric branch and C and L constitute the motional branch. The constants of the stator composite, resonance frequency and anti-resonance frequency as well as equivalent circuit elements can be calculated by using an iterative approach [15]. The impedance curve of each phase of the stator can be used for this evaluation. For identifying a defect, these parameters can be identified and evaluated. Each element in this circuit has a real and imaginary part. For a detailed evaluation, the circuit elements in this model can be transformed to equal real elements in an equivalent circuit model with real values (Fig. 2). The value of the elements in this real model can be calculated from the complex values in Fig. 1. We have

$$Y_d = (C_{0r} + C_{0i}\, j)\, j\omega \tag{1}$$

$$= C_{0r}\, j\omega - C_{0i}\,\omega \tag{2}$$

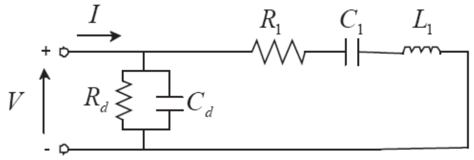

Fig.2. Equivalent circuit model with real value elements. The resistors are frequency dependant.

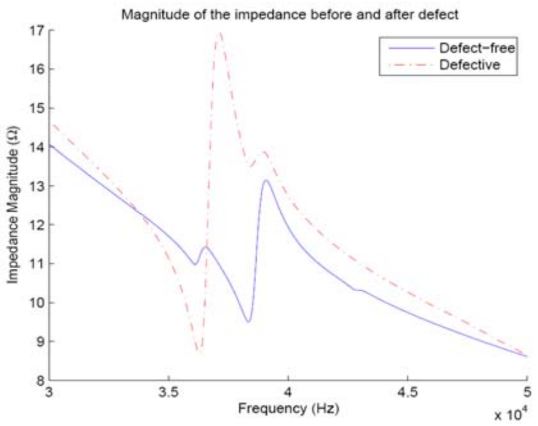

Fig.3(a). The impedance magnitude before and after defect

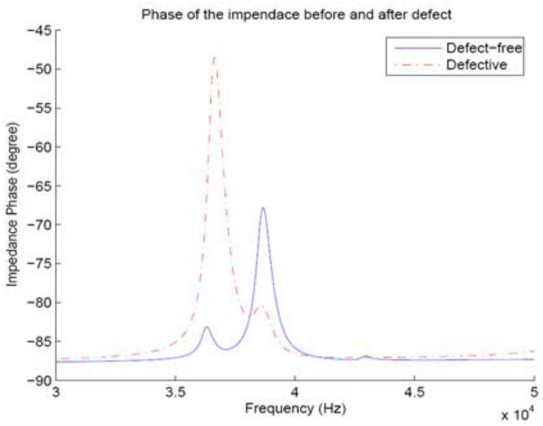

Fig.3(b). The impedance phase before and after defect

where Y_d denotes the admittance of the dielectric branch of the model, C_{0r} is the real part of C_0 and C_{0i} is its imaginary fraction. From (2) the values of C_d and R_d in Fig. 2 can be derived as

$$C_d = C_{0r} \tag{3}$$

$$R_d(\omega) = -\frac{1}{C_{0i}\omega} \tag{4}$$

and for the impedance of motional branch

$$\begin{aligned} Z_m &= \frac{1}{Cj\omega} + Lj\omega \\ &= \frac{1}{C_1 j\omega} + L_1 j\omega + R_1(\omega) \end{aligned} \tag{5}$$

with

$$C_1 = \frac{(C_r^2 + C_i^2)}{C_r} \tag{6}$$

$$L_1 = L_r \tag{7}$$

$$R_1(\omega) = -\frac{C_i + L_i(C_r^2 + C_i^2)\omega^2}{(C_r^2 + C_i^2)\omega} \tag{8}$$

where C_r and C_i denote the real and imaginary parts of C, whilst L_r and L_i denote the real and imaginary parts of L, respectively. The resistance R_d in the dielectric branch is directly linked to dielectric losses and R_1 in the motional branch is related to the mechanical losses (motional losses). These resistors are frequency dependent which complies and verifies the results of Gonzalez *et al.* [16]. Furthermore, C_d represents the capacitance of the composite capacitor (dielectric capacitor), L_1 is related to the mass of the structure and C_1 is associated to the compliance tensor [13]. Occurrence of a change in each of the elements, comparing to the values in defect-free situation, monitors the change in the relative physical parameter. In the next section, free stator of a multilayer piezoelectric motor is used to evaluate the presented method.

C. Verification

The phases are excited separately through wires which are soldered on the stators. Various sources can make a defect on the stator. Physical damage, delamination of the stack, electrical shock, etc. can be the causes of a defect in the multilayer structure of the composite. The impedance of phases of the free stator were measured after the manufacturing of the stator. After four months, vibration measurement tests with an ultrasonic vibrometer were showing that the stator is not capable of producing clear traveling waves anymore. When the impedance curves of the phases of the free stator of the multilayer piezoelectric motor are available before and after the defect, the method can be examined to evaluate the causes of the defect and performance degradation.

C.1. Scenario 1 - Delamination

In Figs. 3(a) and 3(b), the impedance curves of Phase A of the stators, before and after occurring the defect is shown. The frequency range of 30kHz and 50kHz is selected which includes only one mode of the vibration. The solid line presents the defect-free situation whereas the dashed line presents the defective impedance curve. Also, the calculated values of the composite constants and equivalent circuit parameters for both cases are tabulated in Table I. Figs. 3(a) and 3(b) show that an abrupt change in the resonance and anti-resonance frequencies has happened and they are decreased. Also it can be observed in Table I that C_1 is increased which means the stiffness of the composite is decreased. Many literatures [17]–[19] propose that these phenomena occur because of delamination in case of multilayer composites. Furthermore, Zou *et al.* in [20] states that delamination increases the damping of the structure. Also Chrysochoidis *et al.* [19] presents that the damping in the delaminated specimen changes because of variations in effective damping and stiffness properties in the delaminated sub-laminates, and friction and impacts between the crack faces. But both literatures agree that the behavior of damping is more sophisticated and is a challenging subject of research. The impact of the defect on the damping is presented in Fig. 4(a). The damping is increased in lower frequencies but its overall behavior is

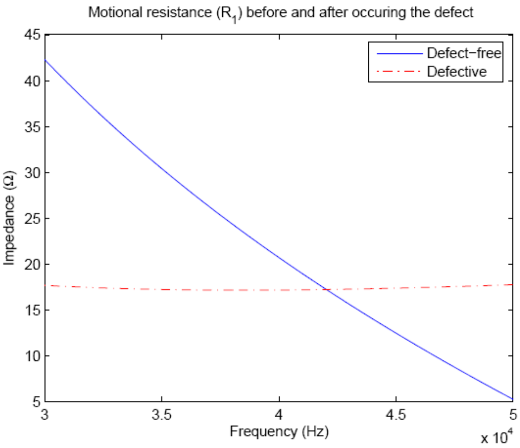

Fig.4(a). Defect in the composite has changed the motional resistance.

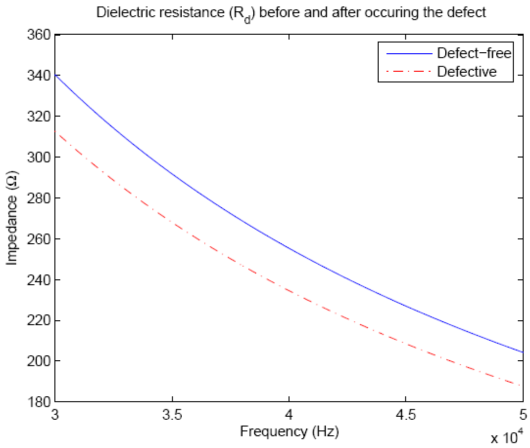

Fig.4(b). Defect in the composite has changed the dielectric resistance

highly altered. The delamination causes changes in the dielectric capacitance of the composite. Delamination can be considered as a change in the distance between laminae which reduces the overall dielectric capacitance of the structure. The variation of C_d before and after occurring the defect verifies that a delamination is happened in the composite and has caused the variation of the impedance. Putting all the results together, we conclude that delamination has occurred during 4 months which shows poor manufacturing of the structure.

Table I. The composite parameters and equivalent circuits elements for defect-free and defective free stators

Parameter	Defect-free Value	Defective Value	Unit
f_s	$38595+350j$	$36504+349j$	[Hz]
f_p	$38717+353j$	$36755+361j$	[Hz]
C_d	3.6751×10^{-7}	3.5096×10^{-7}	[F]
C_1	2.3360×10^{-9}	4.8600×10^{-9}	[F]
L_1	0.0073	0.0039	[H]

C.2. Scenario 2 – Mechanical Damage

The impedance curves of Phase B of the stator, before and after occurring the defect, are presented in Fig. 5. The impedance curve again has changed here and a reduction about 200hz can be observed. High change in the value of L_1, presented in Table II, shows an abrupt variation in induction of the motional branch. Therefore it is concluded that the mass of the composite has been changed. This hypothesis is verified by taking a close look on the surface of the phase B which shows that a large amount of soldering material is used. On the other hand, the increased amount of soldering material on the stator has increased the stiffness. The change in the value of C_1 has changed the dielectric resistance of the composite asserts this conclusion. These changes in the stiffness and mass alter the series resonance frequency. After reviewing the history of the changes made on the product and optical observations, it is concluded that careless re-soldering of the contact wires on the stator has caused the defect.

D. Conclusion

In this paper, a new model based method for defect detection in the stator of a ultrasonic piezoelectric motor was presented. The method is a non-destructive method and is based on the equivalent circuit modeling approach and impedance measurement. By comparing the parameters of the equivalent circuit before and after the defect, the type of the defect can be identified.

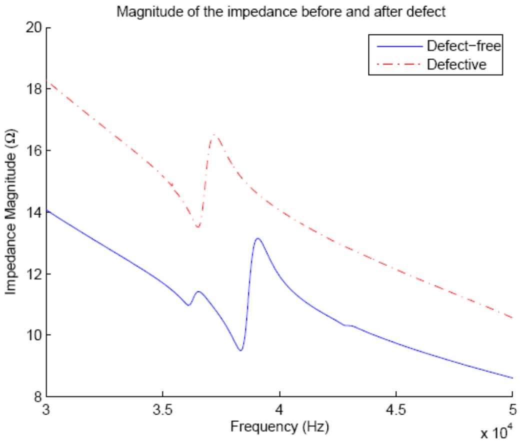

Fig.5(b) Impedance magnitude before and after defect

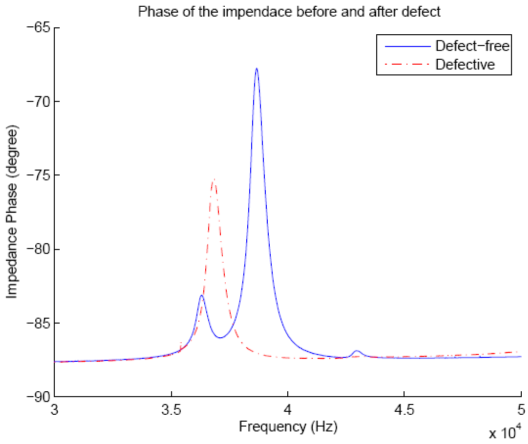

Fig.5(b) Impedance phase before and after defect

Table II. The composite parameters and equivalent circuits elements for defect-free and defective free stators

Parameter	Defect-free Value	Defective Value	Unit
d_{31}	$2.1\times10^{-10}+2.6\times10^{-12}j$	$1.5\times10^{-10}-4.7\times10^{-12}j$	[C.N^{-1}]
f_s	$38596+325j$	$36784+345j$	[Hz]
f_p	$38734+337j$	$36859+346j$	[Hz]
C_d	3.6427×10^{-7}	2.8876×10^{-7}	[F]
C_1	2.612×10^{-9}	1.1746×10^{-9}	[F]
L_1	0.0065	0.016	[H]

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