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THE IMPEDANCE SIGNATURE METHOD FOR IMPEDANCE-BASED STRUCTURAL HEALTH MONITORING

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The electromechanical impedance technique uses piezoelectric transducers (PZT) bonded to the structure of interest for developing structural health monitoring system. In the present work a new method based on the measure of the slope of piezoelectric susceptance is presented. The overall change in impedance shift at different values of temperature and frequency, for given experimental configuration: beam fixed by only one vice, and with two vices on the beam, are graphically presented. Variation with temperature of the imaginary part of the impedance signature as function of frequency at different temperatures is also investigated.

Keywords: piezoelectric transducer (PZT); structural health monitoring (SHM); electromechanical impedance (EMI); temperature.

1. Introduction

Sensors included in a structural health monitoring system are often affixed to structures as a means of identifying structural defects. Health monitoring of aging structures is a major concern of the engineering community. The case of aging aerospace structures, which have been operating well beyond their initial design life is just an example. The durability and health monitoring of such structures constitute the subject of extensive research in many universities, government labs, and industry. This area is considered of new and innovative approaches.

Conventional passive sensors allow the investigation of load and strain history. In contrast, active sensors are able to interrogate the structure (e.g., through elastic waves) acting as both transmitters and receptors. Considerable effort is being currently directed towards (a) development of new and better nondestructive inspection (NDI) techniques; (b) improving the inspection and maintenance procedures; (c) the development of specialized health monitoring sensors; and (d) the construction of automated health-monitoring systems.

The electromechanical impedance (EMI) method uses a piezoelectric (PZT) sensor that is bonded to the inspected host structure. Due to piezoelectric effect the electrical response of a piezoelectric transducer is related to mechanical

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response of the sample to which the transducers is attached. The general constitutive equations of linear piezo-electric material behavior [1] describe a tensorial relation between mechanical and electrical variables(mechanical strain, S_{ij}, mechanical stress, T_{kl}, electrical field, E_k, and electrical displacement D_j) in the form:

$$\begin{aligned} S_{ij} &= s^{E}_{ijk} T_{kl} + d_{kij} E_k \\ D_j &= d_{jkl} T_{kl} + \varepsilon^{T}_{jk} E_k \end{aligned} \tag{1}$$

where s_{ijkl}^{E} is the mechanical compliance of the material measured at zero electric field (E = 0), ε_{jk}^{T} is the dielectric permittivity measured at zero mechanical stress (T = 0), and d_{kij} is the piezoelectric coupling between the electrical and mechanical variables. The *direct piezo-electric effect* is reflected in the second equation, while the first equation refers to the *converse piezo-electric effect.* The *mechanical impedance method is a damage detection technique* pioneered by Lange [2] and Cawley[3].

An impedance-based sensor diagnostics model uses a mass-spring-damper system to come up with an expression revealing that the electrical admittance of a PZT patch $Y(\omega)$ is a combination of the structure's mechanical impedance $Z_s(\omega)$ and the electrical impedance of the piezoelectric transducer $Z_a(\omega)$, as follows [4-6]:

$$Y(\omega) = i\omega \frac{wl}{t}\left[\varepsilon^{T}_{33}(1 - i\delta) - d^{2}_{31} Y^{E}_{p} + \frac{Z_a(\omega)}{Z_a(\omega) + Z_s(\omega)} d^{2}_{31} \hat{Y}^{E}_{p}\left(\frac{\tan \kappa l}{\kappa l}\right)\right] \tag{2}$$

are w, l, and t are the width, length, and thickness of the PZT, ε the dielectric constant of the PZT, δ the dielectric loss factor for PZT, d the piezoelectric coupling constant, and Y_p^E is the complex Young's modulus of the PZT at zero electric field. The κ is the wavenumber of the PZT patch described by:

$$\kappa = \omega \sqrt{\frac{\rho}{Y^{E}_{p}}} \tag{3}$$

where ρ is the material density of the PZT patch. The magnitude of the mechanical impedance of the PZT is generally several orders of magnitude lower than that of the structure they are bonded to. The PZT mass and stiffness are nearly negligible, especially at lower frequencies.

Sensors included in a Structural Health Monitoring system are often susceptible to damage themselves. Many damage detection systems require a large number of sensors distributed over a structure for effective coverage. In our recent work [7] we have studied the influence of the bonding layer on impedance measurements. In this earlier work, the electromechanical impedance (EMI) technique was investigated throughout the electrical impedance measurement of a piezoelectric transducer attached to the investigated structure. The piezoelectric transducer was mounted at the middle of each sample surface. Measurements were conducted using HIOKI Impedance Analyser IM3570. Using the impedance analyzer the electrical parameters were measured up to 5 MHz. The authors of this study investigated the EMI models of piezoelectric sensors incorporating the effects of the boundary layer in the measured electrical admittance signals. The sensitivity of the susceptance, or imaginary part of the admittance measurement, to changes in the bonding layer has also been pointed out in these works. In other work [8] we have reported on experiments carried out in order to remove the temperature changes from impedance measurements in Structural Health Monitoring. We did evaluate the change in the temperature sensitivity as well as the reproductibility of temperature and boundary conditions on electromechanical impedance characteristics of piezoelectric transducers mounted on the structural elements. Due to electromechanical coupling, changes in dynamic characteristics can be seen in electrical impedance of piezoelectric transducers.

In the present work we draw attention on the slope of the susceptance which also changes with temperature. Therefore, a method needs to be in place to determine whether a slope change is due to a type of sensor defect, or whether there is simply a change in the temperature. A model will be introduced to make this distinction. The paper is structured as follows. Section 2 gives a survey on the experimental setups and previously reported results. In this section we recall from Ref.8 the experimental procedures used to investigate the influence of temperature and boundary conditions on EMI characteristics of the piezoelectric transducer mounted on structural elements. Parameters such as resistance, reactance, impedance, and conductance were measured and determined as function of frequency. For completeness we reproduce the overall change in impedance shift at different values of temperature and frequency, for given experimental configuration. In this section we complete our analysis studying the behavior of the slope of the susceptance which also changes with temperature. A numerical method is proposed to determine whether a slope change is due to a type of sensor defect, or whether there is simply a change in the temperature. To obtain data the susceptance, *B*, is found from the real and imaginary impedance components. Variation with temperature of the imaginary part of the impedance signature as function of frequency at different temperatures is investigated. Section 3 gives concluding remarks and further directions of research.

2. Experimental procedures and results

Here we refer to the experiments[8] conducted specifically to: *a*) compare the stability of electric characteristics of five piezoelectric transducers (PZT) and to chose the suitable one for further impedance analysis, *b*) obtain the influence of different boundary conditions on electromechanical impedance characteristics of the PZT mounted on the structural elements; *c*) obtain the influence of temperature changes on electromechanical impedance characteristics of the piezoelectric transducer mounted on the structural elements. In these experiments the FBG temperature probe was used for temperature monitoring during impedance measurements in temperature chamber.

In these experiments, five Sonox P5 PZT transducers were utilized for measurement of real part of electrical impedance or resistance characteristics. These measurements were performed at different temperatures starting from the room temperature up to 50^{o}C. Measurements of electric quantities for freely hanging PZT transducers in temperature chamber were made regarding resistance shift with temperature. Once determined the most stable electric characteristics, the corresponding PZT sensor was mounted on an aluminium alloy beam of 18.5cm length and 2cm width using cyanoacrylate adhesive. Next, one end of the beam was clamped in the vice and this configuration was inserted into a temperature chamber. This setup was subjected to control heating from 25°C to 50°C with 5^{o}C step. With an impedance analyser (Hioki IM3570)(Fig.1., left) the data was collected for each temperature step, and analysed from the point of view of induced changes observed in resistance Rs (serial resistance) due to the temperature shift. Measurements of electric quantities for freely hanging PZT transducers in heating chamber (Fig. 1, right) were made regarding resistance shift with temperature. The temperature has been measured with a FBG sensor and corrections have been made in the final calculated data results.

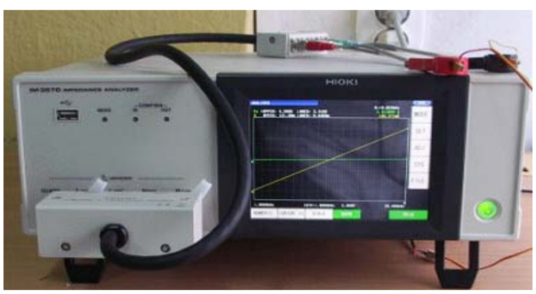

Fig.1. (left) Impedance analyzer used for the EMI technique type IM3570. (right) Heating chamber

The temperature chamber allows for a controlled temperature and pressure conditions. Pressure was maintained at atmospheric values for the duration of testing. The Bragg grating sensors parameters were stored in databases being simultaneously recorded with respect to the Bragg peak shift. The temperature probe sensitivity is +/- 0.05 ^{o}C. In Fig. 2 are presented, comparatively, results for the shift of impedance with temperature at given frequency of 20 MHz.

Once determined the most stable electric characteristics, the corresponding PZT sensor was mounted on an aluminium alloy beam using cyanoacrylate adhesive.

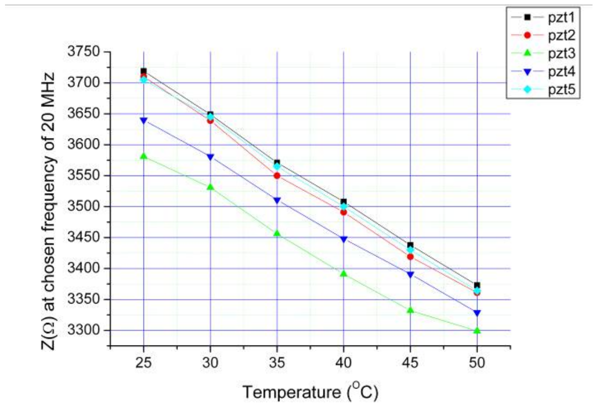

Fig.2. Comparative results for the impedance shift of five PZT transducers tested for their temperature dependence stability in a very narrow frequency range

Next, one end of the beam was clamped in the vice and this configuration was inserted into a heating chamber. With the impedance analyzer the data was collected for each temperature step, and analyzed from the point of view of induced changes observed in resistance Rs (serial resistance) due to the temperature shift. The temperature has been measured with a FBG sensor and corrections have been made in the final calculated data results.

Fig.3. The PZT mounted on aluminium beam: (left) the beam with one vice inside the heating chamber, (right) the beam with two vices

Several tests over amplitude and frequency shift of resistance peaks, Rs, caused by temperature, have been performed for beam with one vice and with two vices, respectively. For completeness, selected results are plotted in Fig. 4 and Fig. 5, respectively. For the beam with one vice (Fig. 4) it can be observed that resistance peak is shifted to the left with increasing temperature. The same situation can be observed for beam with two vices, see Fig. 5. Moreover in Fig. 5 characteristic monotonic amplitude reduction of resistance with increasing temperature can be noticed. Similar situation was noticed in paper [9]. This monotonic behavior does not exist for all peaks which were measured here; see for example Ref. [9].

In the impedance approach to model PZT-structure electromechanical interaction, the analytical model is bilaterally symmetric in both the longitudinal and the width directions. The strains of the PZT are uniform distributed. The selected resonance peaks plotted in Figures 4 and 5 clearly exhibited similar behavior as temperature increases. Fig. 6 gives EMI results from measurements taken in the temperature 25^{o}C from different beam configurations. Comparing these results it can be concluded that support conditions (boundary condition) has very large influence on vibration characteristic and in turn on resistance characteristic of piezoelectric transducer mounted on this structure.

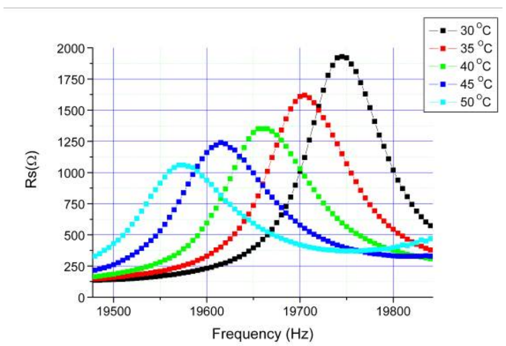

Fig. 4. The influence of temperature on frequency shift of chosen peak for beam with one vice.

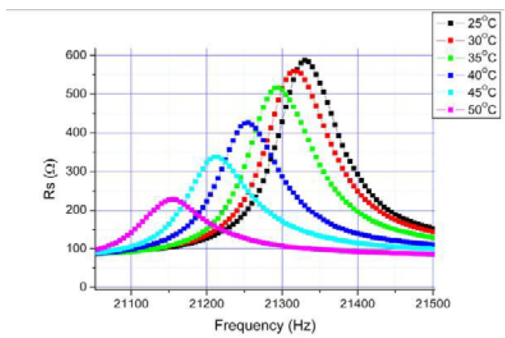

Fig. 5. The influence of temperature on frequency shift of chosen peak for beam with two vices

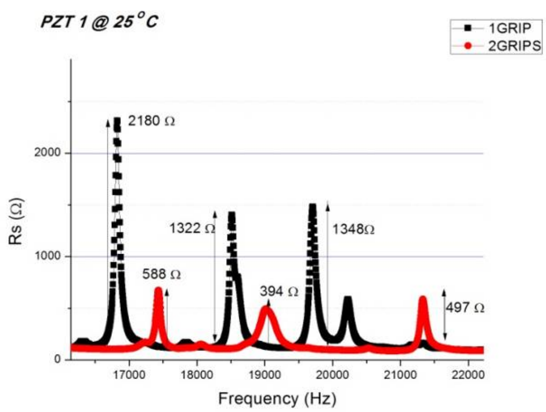

Fig. 6. Comparison of the results for the beam with the two experimental configurations.

Fig. 6 shows the EMI results from measurements taken in the temperature 25°C from different beam configurations. Comparing these results it can be concluded that support conditions (boundary condition) has very large influence on vibration characteristic and in turn on resistance characteristic of piezoelectric transducer mounted on this structure.

In all these earlier studies, the impedance-based sensor diagnostic model is based on the "single impedance method" model that uses a mass-spring-damper system to come up with an expression revealing that the electrical admittance of a PZT patch Y(ω) is a combination of the structure's mechanical impedance and the electrical impedance of the piezoelectric. The magnitude of the mechanical impedance of the PZT is generally several orders of magnitude lower than that of the structure, so the PZT mass and stiffness are nearly negligible, especially at lower frequencies. In the present study we propose a new model and method looking at temperature changes on the imaginary part of the admittance. The research presented here will attempt to address this issue for sensor diagnostics on complex structures in varying thermal environments.

In most cases, assuming that the mechanical impedance is infinity is not unrealistic as the sensors are generally much smaller compared to the structures they are bonded to. The magnitude of the mechanical impedance of the PZT is generally several orders of magnitude lower than that of the structure, so that the PZT mass and stiffness are nearly negligible, especially at lower frequencies.

The static approximation for the admittance of an unbonded patch (sensor dynamics are neglected) is given by the following relation [10]:

$$\mathrm{Y}_{free}(\omega) = i\omega \frac{wl}{t}\left[\varepsilon_{33}^{T}(1-i\delta)\right] \tag{4}$$

Assuming that the mechanical impedance $Z_s(\omega)$ in Eq. (2) goes to infinity, the equation simplifies to:

$$\mathrm{Y}(\omega) = \mathrm{Y}_{free}(\omega) - i\omega \frac{wl}{t}\left[d_{31}^{2}\mathrm{Y}_{p}^{E}\right] \tag{5}$$

Thus, by bonding the PZT to a structure one should expect a reduction of the admittance by a factor of $(wl/t)[d_{31}^{2}Y_p^{E}]$ and these changes only influence the imaginary part of the admittance, or susceptance *B*.

Data collected with the impedance analyser were used to obtain data useful for this study. Using a laptop operating a LabView code, the real and imaginary components of the impedance are collected. The susceptance *B* is found from the real and imaginary impedance components using the equation:

$$B = \mathrm{Im}(\mathrm{Y}) = \frac{-X}{R^2 + X^2} \tag{6}$$

where *Y* is admittance, *X* the imaginary component of the impedance, and *R* the real part of impedance. The imaginary component, X (in jΩ units), is plotted in

Fig. 7 versus the entire frequency interval for beam mounted on one and two vices, respectively. Fig. 8 shows more details on the behaviour of the imaginary part of the impedance signatures at different temperatures for selected resonance peak as shown in Fig.6. Comparative results are presented in Fig. 9 for two boundary conditions used in present experiment.

In Fig. 10, three separate susceptance measurements with the beam mounted on two vices are shown. All three of the curves sit directly on top of one other and show little variation. A similar set of measurements were also performed with the beam mounted on one vice. Fig.10 reveals that the slope of the susceptance increases, for beam with two vices, almost linearly with temperature in the range considered here. Comparing these results with those obtained from measurement of the beam with one vice one concludes that the slope of the susceptance could provide a useful method for characterizing the PZT sensors with respect to temperature and boundary conditions.

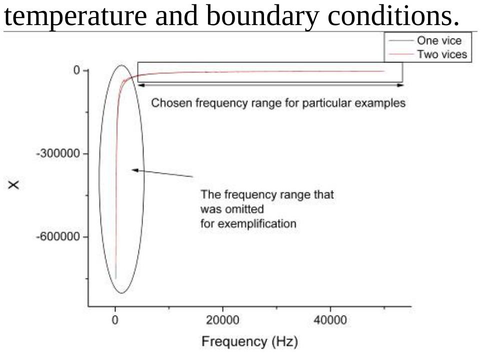

Fig.7. Variation with temperature of the imaginary part (in jΩ units) of the impedance signature as function of frequency at different temperatures

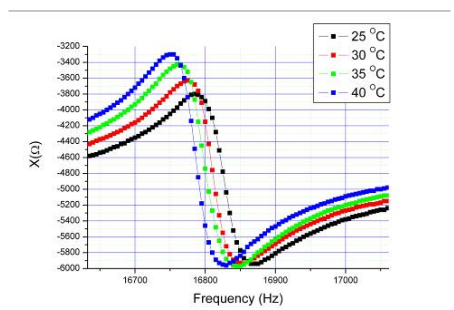

Fig.8. Variation with temperature of the imaginary part (in jΩ units) of the impedance signature for selected peak as function of frequency (beam mounted on one vice).

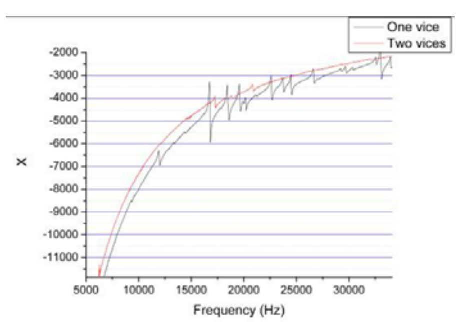

Fig.9. Comparative results on the variation with temperature of the imaginary part (in jΩ units) of the impedance signatures as function of frequency.

Fig. 11 shows, for comparison purposes, the susceptance (in Ohms-1 units) variation with frequency (in Hz units) at constant temperature of 40oC. The same basic trend of the susceptance slopes showing typical results of signatures for the investigated PZT sensor is observed. As expected, the sensor mounted on the beam with one vice shows a susceptance slope below the slopes of the sensor mounted on beam with two vices.

In all experiments studied in the present work, at every temperature from which data was collected, the susceptance is observed in the range of 100 50 kHz for each PZT. Previous studies [4, 6] have revealed that slope of the susceptance is linear under 20 kHz, and Eq. (5) is generally considered valid under frequencies of 20 kHz.

In the case of studied experiments, it seems that the most obvious solution is to model the slopes of the sensor susceptances versus temperatures seen in Fig. 10 using a linear least-squares fit and to use these results in order to base a model for extracting separate effects of temperature and boundary conditions, respectively. This work is in progress.

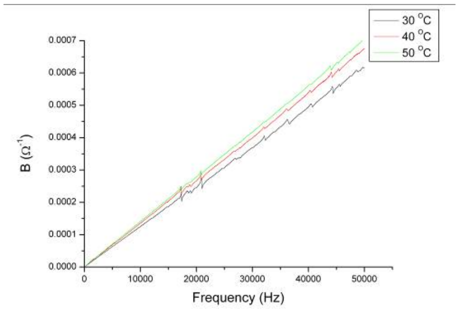

Fig. 10. The susceptance (in Ohms^{-1} units) as function of frequency (in Hz units) for the PZT mounted on aluminium beam (the beam with two vices).

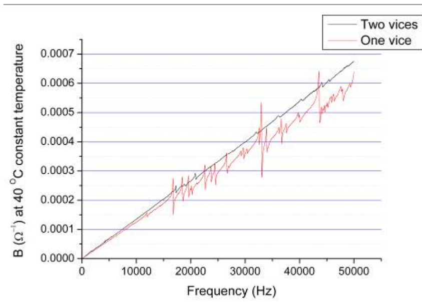

Fig. 11. Comparing results at constant temperature representing the variation with frequency (in Hz units) of the susceptance (in Ohms^{-1} units) as output from experiments.

3. Conclusion

The paper presents results from an extensive set of measurements on EMI using combined methods with PZT transducers and FBG sensors in order to provide more insight in Structural Health Monitoring. Authors studied the influence of boundary condition and temperature changes on electromechanical impedance characteristics of the piezoelectric transducer mounted on the structural elements. Due to electromechanical coupling changes in dynamic characteristics can be seen in electrical impedance characteristics of piezoelectric transducer.

Two conclusions follow to the present work: a) consistent decrease of frequency of the peak with increase of temperature in the frequency interval considered regardless the type of boundary conditions used; b) the appearance of different resonance peaks for different boundary conditions of the beam. In all present investigation, the physical quantities measured and plotted for selected resonance peaks clearly exhibit similar behaviour as temperature increases.

From the analysis of the imaginary part of the impedance signature one concludes that the slope of the susceptance could provide a useful method for characterising the PZT sensors with respect to temperature and boundary conditions. This work is in progress.

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R E F E R E N C E S

[1]. *V. Giurgiutiu, A. Zagrai and Jing Jing Bao* , " Pezoelectric Wafer Embedded Active Sensors forAging Aircraft Structural Health Monitoring", Journal of Intelligent Material Systems and Structures, **vol. 11** , no.12, 2000, pp 959 – 976.

[2]. *C. Lange.,*"Characteristics of the impedance method of inspection and of impedance inspection transducers, Sov. J. NDT. 1978, pp.958-966.

[3] *P. Cawley*, 'The impedance method for nondestructive inspection" NDT *International*, **vol. 17**, no. 2, 1984, pp. 59-65.

[4]. *G.Park, C.R. Farrar, F. Lanza,, D. di Scalea, S. Coccia*, "Performance assessment and validation of oiezoelectric active sensors in structural health monitorig, Smart Materials and structures **vol. 15**, 2006,pp 1673-1683

[5] *C. Liang, F.P. Sun and C.A. Rogers*, " Coupled electromechanical analysis of adaptive material system-determination of actuator power consumption and system energy transfer. Journal of Intelligent Materinal Systems and Structures**, vol 5**, 1994, pp 12-20.

[6] *G. .Park, C.R. Farrar, A.C. Rutherford, A.N. Robertson,"* Piezoelectric active sensor self-diagnostics using electrical admittance measurements. Journal of Vibration and Acoustics **vol.2**,2006,pp 469 -476.

[7] *P.W. Malinowski, T. Wandowski, A Stancalie and W.M. Ostachowicz*, "Application of EMI technique for characterisation of composite adhesive bonds", Paper presented at 6th International Symposium on NDT in Aerospace, 12-14thNovember 2014, Madrid, Spain,www.ndt.net/app.aeroNDT2014

[8] *A Stancalie, D Sporea, P Malinowski, M Mieloszyk, S Opoka, T Wandowski, and W Ostachowicz*, "Influence of support conditions and temperature on the EMI characteristics" Paper presented at 11th International Conference on Damage Assessment of Structures, DAMAS2015, Ghent University, Belgium, 24-26 August 2015, IOP Journal of Physics Conference Series, in press.

[9] *T. Siebel, M. Lilov*, "Experimental Investigation on Improving Electromechanical Impedance based Damage Detection by Temperature Compensation, in DAMAGE ASSESSMENT OF STRUCTURES X, PTS1 AND 2. Book series: Key engineering materials **2013,** 569-570, 1132-1139.Ed. Basu B.

[10] *J. Sirohi., I. Chopra*, "Fundamental behaviour of piezoceramic sheet actuators". Journal of Intelligent Material Systems and Structures **vol 11**,2000, pp 47-61.