Characterisation of influence factors of the resonant frequency of a Langevin transducer

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RESUMO: A levitação acustoforética tem um grande potencial no estudo de fenômenos que requerem manipulação sem contato. O uso de transdutores de Langevin esbarra em grandes variações na frequência de ressonância do sistema. Revisão bibliográfica mostrou quais são os principais fatores para esse comportamento. Este artigo investiga cada fator isoladamente. Explicações são propostas para cada um desses e comparadas com a literatura disponível. Estudos adicionais na área são sugeridos. Um método de calibração para a frequência de ressonância é proposto.

PALAVRAS-CHAVE: transdutor, ressonância, caracterização

ABSTRACT: *Acoustophoretic levitation has a great potential in study of phenomena which require contactless handling. The use of Langevin transducers for such end face large variations in the system's resonant frequency. Literature review revealed key factors which cause such behaviour. This article investigates each factor in turn. Explanations for each are proposed and compared with existent literature. Further studies in the subject are suggested. A calibration method for the resonant frequency is proposed.*

KEYWORDS: ***transducer, resonance, characterisation, (italic format)***

INTRODUCTION

Nowadays acoustophoretic levitation is of interest when considering applications which involve contactless manipulation of objects. Some examples of applications are the study of physical phenomena and bioprocesses, such as handling genetic material (Foresti *et al.*, 2013) or the study of surface tension in liquids (Lee *et al.*, 1994).

One of the most commonly used pieces of equipment in the field is the Langevin transducer (Foresti *et al.*, 2013, Field and Scheeline, 2007, Andrade *et al.*, 2014, Wie and Wei, 2002), which generates ultrasonic acoustic waves when excited by electrical stimuli. In their final year project at the University of Bristol, Bloxham *et al.* (2014) designed a Langevin transducer, shown in Fig. 1,for a tasting experience, basing their design in the one proposed by Foresti *et al.* (2013).

Figure 1 - Langevin transducer before assembly

During the process of tuning the resonant frequency for the transducer, however, it was noted that every new transducer assembled had a different frequency of resonance, which also changed over time after assembly in a non-reproducible way. When driven at high power, it is expected that such transducers have high non-linearities, and a resonance which is dependent on both time and temperature (Guyomar *et al.*, 2011).

For the use in transducer arrays, it was necessary that the resonant frequency would not vary more than 0.1% between adjacent transducers (Field and Scheeline, 2007). This leads to a need to understand and be able to predict how the frequency shifts and which parameters are most dominant, with the aim to develop a calibration method for the transducers. This article aims to define these factors and explain them.

METHODOLOGY

The literature review showed that the main factors which influenced in the resonance frequency are the masses involved, the elastic properties of the piezoceramic material temperature and the prestressing applied to the central bolt. It has also shown that, when driven at high voltages, the resonance frequency is time-dependant (Foresti *et al.*, 2013).

The time dependency was the first to be estimated, subjecting the transducer to 30 minutes-long and 2 hours-long periods of continuous usage.

Morgan (2013) states that when piezoelectric elements are subjected to prestressing greater than30 MPa, the relationship between coupling factor and stress, or between capacitance and stress, may vary in a non-reproducible manner. This lead to a revision of the calculations done by Bloxham *et al.*(2014). They used the relationship shown in Eq. (1) to estimate the static stress applied on the piezoelectric elements with respect to the torque to which the central bolt was fastened.

$$\tau = F_t\left[\frac{d_2}{2}\left(\frac{\mu}{\cos\theta_1}+\tan\theta_2\right)+\mu_n\frac{d_n}{2}\right] \qquad (1)$$

Where Ft is the tension load produced on the bolt, τ is the torque, d_2 is the mean bolt thread diameter, μ is the friction coefficient between the bolt and the horn, θ_1 is the half angle of the screw thread, θ_2 is the lead angle of the thread, μ_n is the friction coefficient between the bolt head and the backing mass and d_n is the diameter of the bolt head.

However, according to Shigley (2007), the relationship between the torque and the force applied by the central bolt is given by Eq. (2). The relation between applied prestress and torque can be derived using the definition of stress, giving Eq. (3).

$$\tau = K \times d \times F_t \qquad (2)$$

$$\tau = K \times d \times \sigma_c \times A_c \qquad (3)$$

Where K is a friction constant which may be assumed to equal 0.2 for most applications (Shigley, 2007), d is the bolt nominal diameter, σ_c the stress on the piezoceramic and A_c the cross-sectional area.

The effect of Temperature on the transducers had to be modelled, as Foresti *et al.*(2013), Andrade et al. (2014) and Field and Scheeline (2007) all agree that it is a major factor in determining the resonance frequency. The transducer was then subjected to periods of slow heating, and the temperature and resonance frequency noted. The data was later on processed to determine mathematical relations of these values.

The transducer in question can be modelled by a mass-spring-damper system with two degrees-of-freedom. The effects of mass on the resonance frequency of such system are abundantly explained in the literature, and are governed by Eq. (4) (Meirovitch, 2001):

$$\boldsymbol{M} \times \ddot{\boldsymbol{x}}(t) + \boldsymbol{C} \times \dot{\boldsymbol{x}}(t) + \boldsymbol{K} \times \boldsymbol{x}(t) = \boldsymbol{F}(t) \quad (4)$$

In which **M, C** and **K** are the mass, damping and stiffness matrices, while $\boldsymbol{x}(t)$, $\dot{\boldsymbol{x}}(t)$ and $\ddot{\boldsymbol{x}}(t)$ are the displacement vector and its first and second time derivatives.

Experimental setup

The transducer was connected to an Agilent 33220A signal generator, and the amplitude of the centre of the horn measured by a Laser Doppler Vibrometer (LDV), composed of a Polytec OFV-505 and a Polytec OFV 2700 ultrasonics vibrometer controller. The signal output of the LDV was then analysed in an Agilent DSO1024A oscilloscope, as shown in Fig. 2.

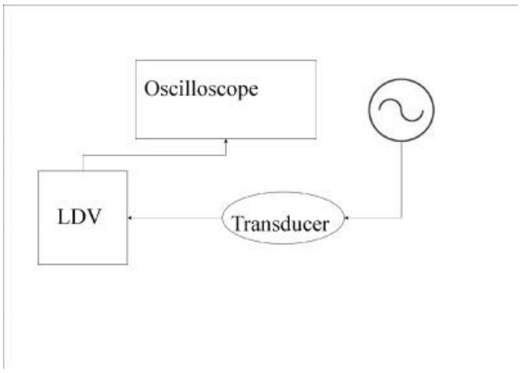

Figure 2 - Schematic drawing of the experimental setup

In order to find the resonant frequency, the input signal frequency was swept, finding the interval over which the amplitude of the output signal was maximum and recording the value of resonance as the middle value of said interval.

For the temperature tests, the transducer was enclosed in a cardboard box with a HS50 heating plate, and the air temperature close to the transducer was measured by a digital thermometer, with precision of 0.1ºC. The air temperature was slowly risen in steps of approximately 1ºC, which allowed time for the Langevin transducer to reach thermal equilibrium before measuring the resonance frequency.

The results obtained in the LDV were confirmed by analysing the impedance of the transducer. A Cypher Instruments C-60 Impedance-Phase-Amplitude analyser was used for the measurements.

RESULTS AND DISCUSSION

Prestressing calculations review

The review of the prestressing calculations revealed that the prestress applied to the piezoelectric elements was above 30 MPa, and was probably causing a number of non-reproducible variations observed in the working transducer. A new transducer was assembled, respecting the maximum according to Eq. (3) and presented a much more constant behaviour.

Time variation of resonant frequency

The first short (30 minutes-long) tests were run to determine the variation in time of the frequency. The results are shown in Fig. 3.

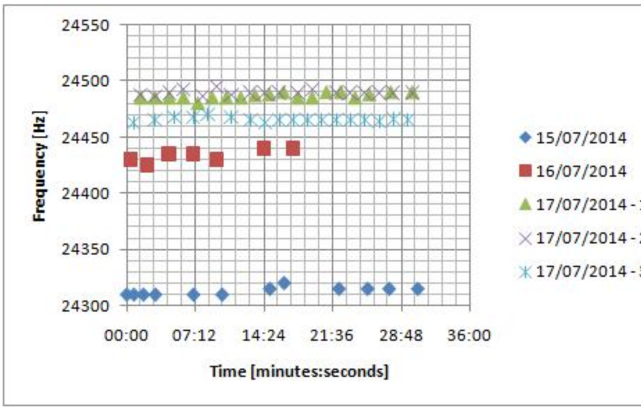

Figure 3 - Results for resonant frequency test without any heating

The results of the long-run test (2 hours-long) are shown in Fig. 4, realised on the 18 July 2014.

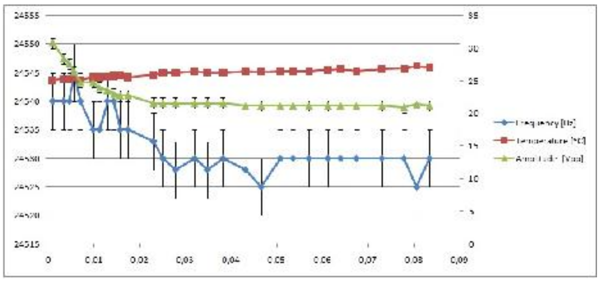

Figure 4 - Long run test results

These graphics show a tendency of the systems to resonate near 24.5 kHz, which is corroborated by the impedance test shown on Figs. 5 and 6.

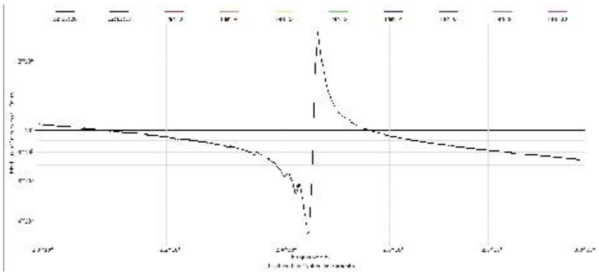

Figure 5 - Impedance versus frequency results

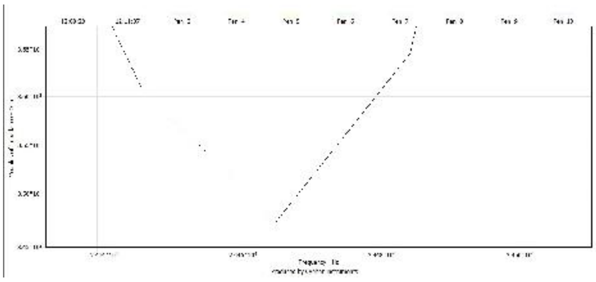

Figure 6 - Detail showing the minimum impedance

Temperature Tests

The temperature test results are shown in Fig. 7.

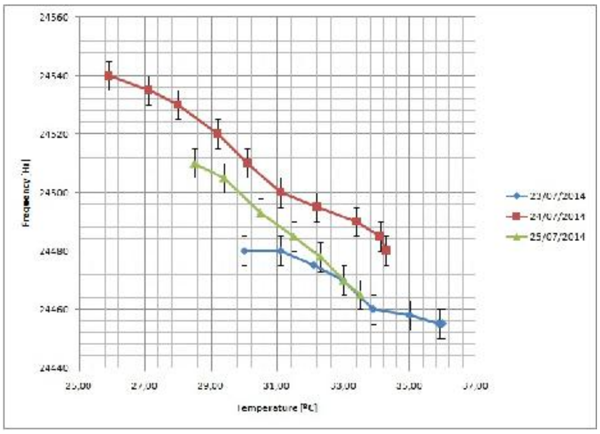

Figure 7 - Frequency versus Temperature graphic

It becomes very clear from Fig. 7 that the relation between temperature and resonant frequency may be approximated by a linear function, with a constant angular coefficient and variable linear coefficient. The angular coefficient may be estimated to be around -7 Hz/ºC, using the least square minimum method in each test separately. It is also interesting to notice that, when considering the temperature effect, the drop in resonant frequency present in the long run test (Fig. 4) is explained.

This kind of relationship may be explained by changes in temperature, because they introduce thermal deformation of the components and also changes in the permittivity of the piezoelectric elements, which varies linearly with temperature(Wang *et al.*, 1998).

It is to be noticed that from a certain point in time, the variation in resonant frequency did not exceed 25 Hz for a given temperature, remaining very near the minimum impedance of the transducer and definitely in the impedance range predicted by Morgan (2013).

The fact that the transducer still varies its resonant frequency from day to day may be explained by a "warm-up" effect, in which the piezoceramic's Young's modulus change with time. Due to the constant application of stress over several days, the ceramic's crystalline structure will go through several discordance movements (Callister Jr., 2000), which will harden the material and hence increase the stiffness and resonant frequency.

CONCLUSION

All the factors which have an influence on the resonant frequency of a Langevin transducer have been observed and their influence determined. Specifically, the time during which the transducer is used and the temperature of operation have the biggest effects on it, as predicted by literature.

The advances made allow the development of a calibration method for choosing the resonant

frequency, by changing the masses involved in the system.
The author suggests as subject of further study the proposed explanations, i.e. the reasons why the resonant frequency shifts with time and temperature.

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RESPONSIBILITY STATEMENT

The author is the only responsible for this article.