Dynamic characterization of an amplified piezoelectric actuator

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Abstract:
The characterisation of piezoelectric actuators in dynamic operation is critical to ensure both the functionality in the application and the survival of the actuator. Unfortunately little data is available. This paper presents a simple approach for characterisation and for the evaluation of the two main limitations of an actuator: voltage and stress. The approach is applied to an amplified piezoelectric actuator without load. The amplified actuator is based upon low voltage piezoelectric ceramic multilayer stacks for systems requiring lighter actuators with temperature stability and high resonance frequency. Experiments demonstrate that a simple first-order model approach can be used, although the parameters, in particular stiffness, are affected by non-linearity. Nevertheless, such a model can be used to evaluate the operating envelope of an actuator in a given dynamic configuration. If it should be performed in a systematic way, this approach requires additional parameters and characterisation from the suppliers.

Keywords: Amplified Actuator, Piezoelectric Actuator; Strain Limits; Dynamic Characterization

Introduction

Piezoelectric actuators are often the preferred choice for highly dynamic applications because of their low inertia and high stiffness, leading to fast response. Dynamic applications include for example fast tuning and steering of optical systems, fuel injection or active vibration control.

The static performance of piezoelectric actuators has been studied extensively [1, 2]. On the other hand, suppliers of piezoelectric devices provide only little information about dynamic characteristics of actuators. Usually a first unloaded resonance frequency is indicated, in most cases in free-free configuration which is rarely representative of how the actuator will be used. Response time is sometimes specified, however this is for very particular conditions. This makes it difficult for the designer to evaluate the limits of an actuator solution and its applicability to a given technical challenge.

The target of this paper is to analyse the dynamic characteristics of a piezoelectric actuator, applied to the example of an amplified actuator, trying to derive an approach and tools usable by designers to estimate and validate their choice. Experimental results are presented and compared to a theoretical approach.

The approach is applied to Noliac’s amplified piezoelectric actuator family NAC26xx (Fig. 1) [3]. These offer a compact solution with a high resonance frequency. The multilayer actuator features a low form factor and provides medium stroke and blocking force. The amplified piezo actuator offers push and pull with the same level of performance and it is temperature stable.

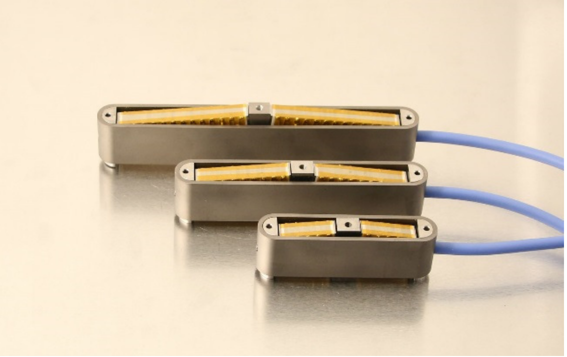

Fig. 1: *NAC26xx amplified actuator family*

Design

The amplified actuator is based upon low voltage piezoelectric ceramic multilayer stacks. The diamond construction makes the actuator mass lower and optimizes stiffness, allowing operation at higher frequency compared to other amplification solutions. The amplified actuator uses four piezoelectric stacks, connected in pairs. Each stack is hinged at its ends and maintained in place with a small angle (Fig. 2). The whole assembly is preloaded through the use of a tension member maintaining the fixed members in place.

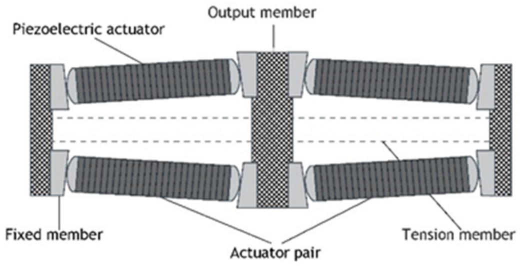

***Fig. 2:** NAC26xx principle*

The actuator is operated as follows (Fig. 3): When the applied voltage is increased on one pair of stacks, it is decreased on the other pair. This contributes to a movement of the output member in one direction. It should be noted that in the case of a free displacement; the tension in the piezoelectric stacks as well as in the tension members (therefore the preload) remains almost constant. This means that strain energy is transferred directly from the stacks to the output instead of being stored in the amplification mechanism. As a result, this amplification method is very efficient. In addition, the structure is not submitted to high bending stress and thus not subject to fatigue.

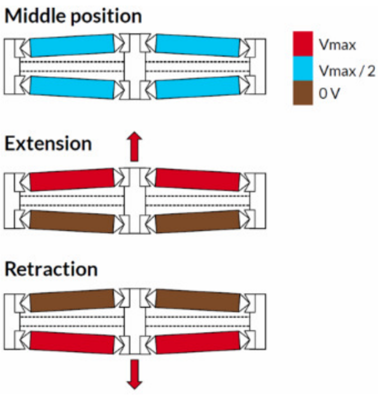

***Fig. 3:** Amplified actuator operation*

The amplified actuator offers push and pull with the same level of performance and it is temperature stable as well. It also offers large strains in static conditions and at resonance.

Theoretical approach

Actuator model

Piezoelectric actuators are usually considered as elastic elements. In a common approach, a piezoelectric actuator is considered as a mechanical spring driving a mass, together with some damping. The piezoelectric effect is modeled as an external force acting on the system. As a result, the system can be described by a first order differential equation (1) and behaves like a driven harmonic oscillator, Fig. 4.

$$m \cdot \ddot{x} = F_{piezo} - k \cdot x - c \cdot \dot{x} - F_{ext.} \qquad (1)$$

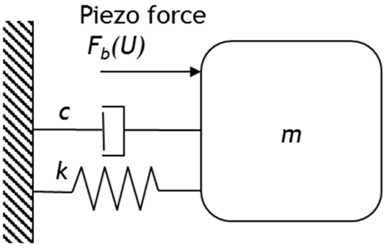

***Fig. 4:** Simple actuator model*

This approach doesn’t include non-linearity such as hysteresis, creep and large signal values of the parameters. However it might be valid for a first estimate. Also, the equations of state must be further processed to indicate the operating envelope of the actuator. Typically, three parameters can limit the operating envelope of the actuator:

Voltage limitation

Piezoelectric actuators are usually tested at a nominal field strength. Even if the ratings can be exceeded in some cases, the recommended operating voltage range recommended by the manufacturer should be respected. Higher field could lead to failure of the ceramic insulation layer or accelerated degradation of the element.

Stress limitation

The second parameter that can limit the operating range of a piezoelectric actuator is mechanical stress. Too high stress can lead to a mechanical degradation of the actuator (cracking) or in extreme cases to a loss of poling. The operating stress range is usually specified by the manufacturer, however it’s up to the designer to ensure that stress remains within acceptable limits at all times, in particular taking into account dynamic loads.

In the case of the amplified actuators NAC26xx, the application of forces outside of the specified range will result in a loss of preload which in turn can lead to unwanted movement of the actuator and ultimately damage.

Thermal limitation

Energy is dissipated in the actuator both in terms of electrical (dielectric) and mechanical losses. Mechanical losses can generally be neglected at low frequency but can be significant around resonance. In any case, this power needs to be transferred to the environment, leading to temperature increase. In extreme cases, the temperature rise can lead to a degradation of the actuator.

Experimentation

Test setup

The tested actuator is NAC2643. Its main characteristics are listed in Table 1.

Table 1: *NAC2643 characteristics*

Operating voltage	200 V
Free displacement	550 µm
Maximum push-pull force	250 N
Stiffness	1 N/µm
Unloaded resonance frequency	1025 Hz

The actuator was driven using a high power driver NDR6880 (300 V max, 10 A peak). A signal generator was used to create a sinusoidal signal. In order to limit the influence of self-heating, a “burst” with 30 waves was used. Position was measured using a non-contact Eddy-current sensor. Typically, the mechanical system takes the first few waves to reach a stable regime. Characteristics (amplitude, phase) can be measured in steady state. After the signal is removed, the vibration is slowly damped-out and the actuator settles after some cycles. An example of a measured waveform is given in Fig 5.

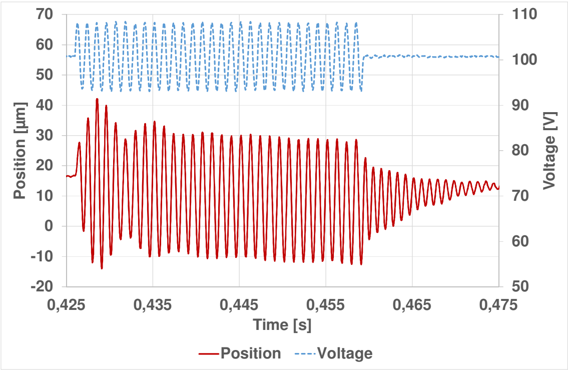

Fig. 5: *Time-domain response at 900Hz*

Results

As previously observed [Cedrat], sub-harmonics are present at certain frequencies and distort the measurement. It is however possible to extract a peak to peak displacement.

The frequency response of the amplified actuator is shown in Fig. 6. Excitation voltage was limited to 15 V to avoid damaging the actuators.

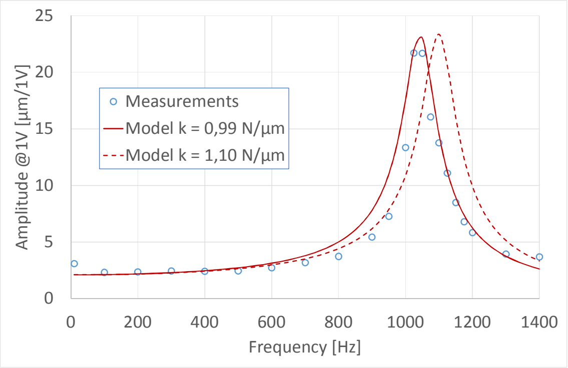

Fig. 6: *Amplitude vs. frequency*

As expected for a first order differential system, amplitude increases significantly around resonance and subsequently drops.

Analysis

It is quite straightforward to fit a first order mechanical system to the measurements, see identified parameters in Table 2. However it is clear from Fig. 6 that the behaviour is not purely a first order. The resonance peak is sharper than expected. The suggested interpretation is that stiffness varies with the amplitude of the motion. At low amplitude, the behaviour can be matched with a certain stiffness, while at high amplitude the apparent stiffness of the system decreases. For the tested amplitude, a decrease of 10% is observed.

Table 2: *Identified first-order parameters*

Stiffness k, low amplitude	1,1 N/µm
Stiffness k, high amplitude	0,99 N/µm
Inertia m_{eff}	23 g
Damping c	13,6 N.s/m
Free displacement @1V	2,1 µm

Nevertheless, a first order system allows a decent fit, in particular below resonance. This is important since around resonance other limitations are observed.

Limitations

As explained above, three limitations can be encountered.

For an operation at the maximum recommended voltage, in a first approach the measurements can be scaled, assuming constant gain.

The stress limit can be estimated by re-writing the expression of the dynamic force (2) to highlight the relation of proportionality between displacement and the inverse of frequency squared (3). In these equations the damping is neglected, but it is possible to include it in case it is significant.

$$F_{dyn} = \pm 4 \cdot \pi^2 \cdot m_{eff} \cdot \frac{\Delta}{2} \cdot f^2 \qquad (2)$$

$$\Delta_{\max} \approx \frac{1}{f^2} \qquad (3)$$

Once a maximum displacement is calculated, it can be converted into a maximum input voltage. The limitations can be plotted, defining the operating range of the actuator (Fig. 7).

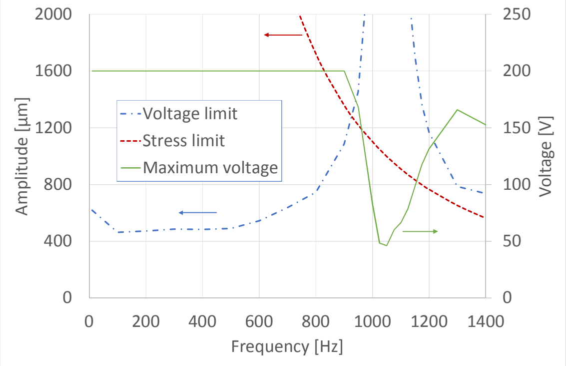

***Fig. 7:** Illustration of the dynamic limits*

Calculations indicate that the unloaded actuator can reach a displacement amplitude of 1200µm just below resonance, after switching to a stress limit. The maximum applicable voltage has to be decreased accordingly.

The thermal limitation was not evaluated, however it is clear that the actuator will heat-up significantly in these conditions, therefore it can only be operated at low duty-cycle.

Discussion

The measurements and analysis presented above can help the designer for the selection of an actuator. It should be kept in mind that the dynamic characteristics of a system depend not only on the actuator, but also on its load. Therefore the designer must add to the model of the actuator a model of the load. Using these assumptions, the impact of an added mass can be simulated. It affects both the frequency response of the system (shift of the resonance frequency) and the stress limit (dynamic force).

Additional stiffness has a significantly different impact. Typically the resonance is increased while displacement is reduced. This induces a more stable behaviour at high frequency. However the thermal limit is usually unchanged and becomes more critical. In any case, a simple first-order system allows the designer to establish the first estimates of the operating envelope of a system.

Conclusions

The present paper present a simple model and approach for the estimation of the operating envelope of an actuator solution. Typically this envelope is defined by three limitations: voltage, stress and thermal.

The model doesn't include non-linearities (creep, hysteresis) so these need to be accounted for during the development phase. However it provides relevant data for a first estimation.

The approach is applied to an amplified actuator NAC2643 without load. Measurements and calculations indicate that the actuator can be operated substantially above its free displacement specification, at frequencies below the first mechanical resonance, up to the point where it switches from a voltage limit to a stress limit.

In order to be applicable, this approach requires additional parameters that are usually not part of actuator specifications.

References

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