Dynamic strain limits of Amplified Piezo Actuators

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Abstract:

It is well known that the Amplified Piezo Actuators (APA) offer large strains in static conditions and at resonance. Because many applications as shakers, anti-vibration and motors would benefit also of large dynamic strain below resonance, the maximum strain of the APA has been theoretically and experimentally investigated in this wide frequency range. The tested actuator is the APA30uXS currently used in the SPA30uXS new inertial micro piezo motor. The maximum strain of the APA30uXS is 33µm in both quasi-static and resonant frequencies. High-level measurements show that between these frequencies, the maximum stroke achieves 45µm, which is 50% larger than the max. static and resonant stroke, in agreement with the model. However, at high level, the main mode is coupled by high level sub-harmonic excitations, as proven by further measurements of hysteresis loops versus frequency. A non-linear model is presented to describe these non-linearities.

Keywords: linear, piezoelectric, actuator, strain, limits, non linear model, APA™

Introduction

High-deformation piezo actuators are wanted in many cases because they allow getting compact low-weight devices. This driver was the reason for the development of the now-famous Amplified Piezo Actuators (APA^{TM}) [1],specially considering embedded applications such as space, optics, etc [2]. It is now well known that the Amplified Piezo Actuators offer large strains in static conditions and at resonance. Typical strains at maximal voltage so 150V achieve from 0.5 to 10%. For example the APA400M is only 13mm long while achieving 400µm stroke, which leads to a strain of 3%. These high static strains are used in micro-positioning applications when compact and robust actuators are requested. The high strains at resonance of APAs achieve similar values, but the requested voltage is strongly reduced with values of 5 to 10V. This property is used for making various narrow-band compact transducers for vibration generation.

However several applications preferably request large strains and large vibration strokes on a large bandwidth. Such applications include anti-vibration systems, shakers for instrumentations and transient motions devices like the inertial piezo motors [2-5]. A previous theoretical analysis anticipated that this high dynamic strain level should be possible thanks to the APA high prestress [3]. Therefore it was deemed useful to check experimentally in detail the capability of the APAs to produce such high strains values in a large bandwidth.

For such a test, the APA30uXS micro actuator was selected, as the key component of the SPA30uXS piezo motor [5]. Modeling and measurements of the dynamic strains of this APA are presented. New limits due to non-linear effects are identified from tests and are investigated by a new theoretical model.

Frequency domains for limits of piezo actuators

Piezoelectric Actuators have several limitations that must be taken into account to properly design the applications. These limits are electrical, mechanical and thermal. The impact of these limits depends a lot of the frequency region the actuators are used (table 1). These frequency regions are governed by the desired function and applications.

Ref	Frequency region	Bandwidth Definition
S	Static & quasistatic (S)	From 0 to $F_{res}/3$
DS	Dynamic Strain (DS)	Between $F_{res}/3$ and Resonance reg.
R	Resonance (R)	3dB-bandwidth around mechanical resonance frequency F_{res}
DF	Dynamic Force (DF)	Frequency above Resonance region
I	S + DS + R + DF	Whole frequency spectrum

***Tab.1**: Frequency regions definition*

Electrical limits of piezo actuators

The maximum applied voltage is limited to 150 V by the insulating layer. Since the thickness of the layer in the multi-layer piezo ceramic (MLA) is 100 µm, it corresponds to an electrical field of 1.5 kV/mm. The applied voltage cannot be decreased under -20 V. Otherwise, the polarization would be reversed.

In Static operations, the lifetime is mainly limited by the combination of DC voltage and humidity, which penetrates through the external insulation layer and leads to a leakage current increase. A larger leakage current can lead to an electrical breakdown.

In Dynamic Strain non-resonant operation (DS region), electrical limits may be encountered. With a margin, the max dynamic voltage is 170vpeak-to-peak. Because of the capacitive nature of the piezo actuators, the higher the frequency is, the higher the current is. This current need may reach the power amplifier limits.

Mechanical limits of piezo actuators

In dynamic operations, especially in resonance region (R), the piezo actuator mechanical stress limits may be encountered, leading to a force limit.

Since multilayer piezo ceramics are laminated and brittle materials, they cannot bear any tensile forces. Bending or twisting moments must be avoided as much as possible, even during the mounting procedure. Tensile forces during dynamic operations or switched operations must also be avoided. To overcome this material limit, a prestress (also called preload) should be applied on the ceramic to maintain it in compression. Therefore a well-defined mechanical prestress is applied in all the Piezo Actuators from Cedrat Technologies [3].

In dynamic conditions, the level of prestress in a piezo actuator is responsible for the limitation of actuator stroke (or its vibration amplitude). Mobile masses generate dynamic forces and stresses that can rapidly damage the actuator if tensile stresses are encountered. Therefore a high prestress is applied in most of APAs to keep the ceramic in compression and get a high dynamic force limit. This is highly beneficial for dynamic applications as shown further.

Tests of APA dynamic strain limits

The impact of voltage and force limits is calculated using a Lump Parameter (LP) Model. This model named COMPACT is implemented on Microsoft Excel. It includes a complete library of APA and PPA actuators and publicly released as a freeware from Cedrat Technologies. The model is able to compute the harmonic responses as transfer functions in terms of Stroke per volt, Force per volt, Admittance, etc. Taking into account the voltage limits and the stress limits of the actuator, it computes its maximal displacement and forces versus frequency.

The selected actuator for the strain limit experiment is an APA30uXS. This micro amplified piezo actuator is completed by a rod on one of end and by a mass m=0,24gr on the other end (Fig 1). This forms the stator of the SPA piezo motor [5]. In this experiment, the rod is firmly clamped while the mass is free to move. This APA30uXS micro actuator features a static stroke of 33µm at 150V, so 0.2µm per volt. As its height is 3.9mm, the max static strain is 0.9%. Its blocked force at 150V is 3.6N. Its stiffness K is 0.12N/µm.

In test conditions, the voltage is varied from 0 to 150V. So the max peak sine voltage is 75V. The free quasi static displacement is 17µm. The quasi static actuation force is 1.65N. This force may be limited in dynamic condition by the internal prestress. Because of the prestress design and the mounting condition, the dynamic force limit is also 1.65N. Applying a safety margin of 30% for the test, the maximum dynamic force is fixed to 1.15N.

***Fig 1** : APA30uXS with a rod (used to fix the actuator) and a mass (free to move)*

The stroke versus frequency has been measured at first at very low excitation voltage level and compared with the LP Model (fig 2). The measured displacement-per-volt frequency response reveals a quasi displacement of 0.2µm/V in the 1kHz region. It also shows an isolated pure mode at a resonance frequency of f_{res}=2.7kHz, with a modal mass M=0,4gr and a Q factor of 20. This mode is due to the stiffness actuator, the actuator modal mass and the free mass. This response is in rather good agreement with the COMPACT LP model. A small discrepancy may be noticed at resonance peak and is explained by non-linearities that occur at resonance due to higher level of strain.

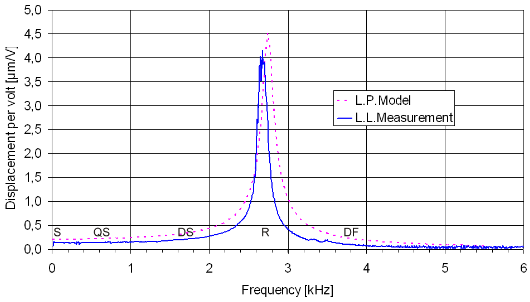

Fig 2 : Measurement of the displacement-per-Volt response compared with COMPACT L.P. Model

To predict the actuator maximal displacement, the force-per-volt transfer function is computed with the LP Model (fig 3). It shows that the resonance amplifies the dynamic forces up to 0.5N/V. If a voltage of 75V is applied, the dynamic force would reach 37.5N which is above the force limit from the prestress. Such a force would break the actuator. To avoid such a failure, the voltage has to be reduced in a frequency region around resonance. The model computes such maximal applicable voltage taking into account the force limits (fig 4). The 75V voltage limit is met below 1.8kHz, then the force limit is achieved, implying a reduction of the max voltage.

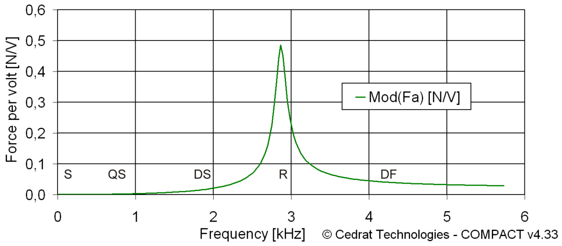

***Fig 3** : Computation of the force-per-Volt response with COMPACT L.P.Model*

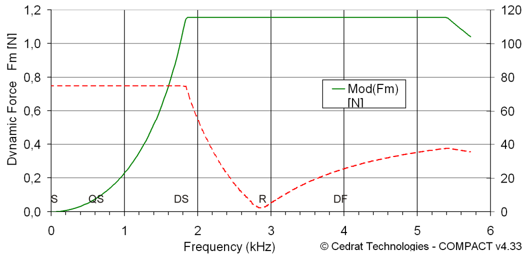

***Fig 4** : Computation of the maximum applicable voltage and the force accounting to the force limit with COMPACT L.P. Model*

The maximum applicable voltage versus frequency from fig 4, so called the Max Voltage law, is used both for theoretical predictions and for test performances. For the prediction, this Max Voltage Law is multiplied to the displacement per volt of fig 2. It determines the peak-to-peak max displacement versus frequency (fig 5) accounting for the voltage limit and the stress limit of the actuator. For the tests on the APA30uXS, the Max Voltage Law is applied to the actuator and the displacement is measured using a laser vibrometer. The measured peak-to-peak amplitude displacement is plotted on the fig 5. A general agreement with theory is obtained.

Of particular interest, the experiment shows the dynamic displacement between static and resonance (f_{res}=2.7kHz) is larger than the displacement in static and at resonance. This was the main goal of the test. At $f_{max\text{-}strain}$=1.8kHz the maximum peak-to-peak displacement is 45µm, which corresponds to a strain of 1.2%. These values are 50% larger than the maximum static stroke and strain, which demonstrates that maximum strains of APA are not obtained at resonance f_{res}=2.7kHz but well below, at $f_{max\text{-}strain}$=1.8kHz. This is the frequency where voltage limits and force limit coincide.

At resonance f_{res}=2.7kHz, the measurement displacement is lower than predicted by the model based on a Q factor of 20. A high level Q factor of about 8 is extracted from this test.

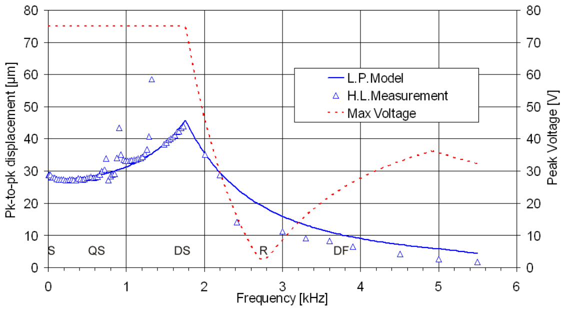

***Fig 5** : Measurement of total displacement vs freq. and applied voltage, compared with L.P. Model*

Non-linearity limits of piezo actuators

The stroke measurement of APA30uXS at max high level presents also an unexpected behavior for specific frequencies. Three spurious modes appear in the high level measurements (fig 6) while they were not at all excited at low level (fig 2). In application they can be filtered but they need to be understood. These frequencies, f_2 = 1.3kHz , f_3 = 0.9kHz and f_4 = 0.7kHz, are the sub-harmonics of the resonance frequency : $f_2 \cong f_{res}/2$, $f_3 \cong f_{res}/3$ and $f_4 \cong f_{res}/4$.

Measurements of hysteresis loops versus frequency (fig 6) have been undertaken to provide some insight.

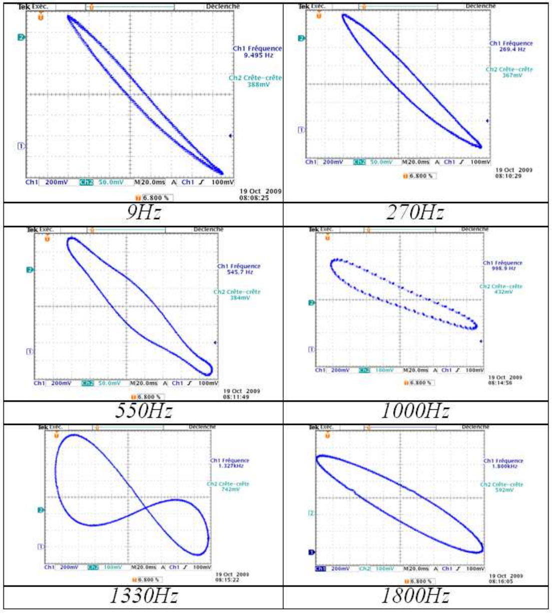
9Hz 270Hz
550Hz 1000Hz
1330Hz 1800Hz

***Fig 6** : Displacement vs voltage at different freq.*

Outside these f_2, f_3 and f_4 frequencies, for ex 9Hz, 270Hz, 550Hz, 1000 and $f_{max\text{-}strain}$=1.8kHz, the hysteresis loops are similar and shows no dephasing. The slope is negative as the actuator contracts when a positive voltage is applied. The hysteresis loop at $f_{max\text{-}strain}$=1.8kHz shows that this is clearly not a resonant frequency because if it were a resonance a phase shift would occur.

Conversely, the hysteresis loop at the f_2=1.3kHz sub-harmonic frequency has a complex shape, not only a phase shift. There are 2 oscillations of displacement per voltage cycle, meaning the vibration is produced at mechanical resonance f_{res} although it is excited at $f_2 \cong f_{res}/2$. This confirms that these spurious modes are coupled by a high level non-linear coupling.

Non linear model of the actuator

To explain the sub-harmonic excitation of resonance at high level, a non linear model is suggested.

The usual linear lumped parameter linear model is based on the equation of dynamics and an excitation from a linear piezo coupling.

$$K.u + M.\ddot{u} + r.\dot{u} = N.V \qquad (1)$$

Noting u the displacement, K the stiffness, M the moving mass, r the resistance in relation with the Quality factor $Q = k/(r.\omega_r)$, ω_r the resonance and N is the force factor form the linear piezo coupling.

The Non Linear model consists in a polynomial series of several orders for the piezo excitation:

$$K.u + M.\ddot{u} + r.\dot{u} = \sum_{k=1}^{n} N_k.V^k \qquad (2)$$

With this equation, the mechanical resonance occurring at ω_r can be excited by either a synchronous or an asynchronous excitation at ω_e.

$$u = u_r.\,e^{j\omega_r t} \quad (3) \qquad V = V_e.e^{j\omega_e t} \quad (4)$$

Approximate solutions of (2) at mechanical resonance with (3) and (4) are identified using excitation frequencies $\omega_{ek} = \omega_r/k$ with $k = 1,\ldots n$:

$$\frac{K}{Q}.u_{rk}.e^{j\omega_r t} = N_k.V_e^{\,k}\, e^{jk\omega_{ek} t} \qquad (5)$$

giving: $$u_{rk} = \frac{Q}{K}.\,N_k\,V_e^k \qquad (6)$$

The solution u_{rk} is the displacement amplitude for a vibration at resonance ω_r due to an excitation at $\omega_{ek} = \omega_r/k$. This vibration amplitude is linear only for the excitation $\omega_{e1} = \omega_r$ at resonance. For the sub harmonic excitation $\omega_{e2} = \omega_r/2$, the vibration amplitude is quadratic with the voltage, etc. It is why at low excitation, the frequency response (fig.2) only shows one excitation mode. However more tests at various excitations V_e are required to check fully (6).

This model also assumes that $N_1 >> N_2 >> N_3 \ldots$

So to further assess this model, an identification of N_1, N_2, N_3, N_4 for centered voltages on 75V has been performed by inverting eq. (6) and using fig 5 data, giving Tab 2 Values that checks previous assumption.

Finally, for testing the model, eq. (2) is used in quasi static to build displacement curve u(V). Accounting for N_1 and N_2 and the high level quality factor Q=8, a good agreement is obtained (fig.7) comparing the model and the measured stroke of APA30uXS.

Excit. rank	1	2	3	4
N_k [N/V^k]	2,68E-02	-7,73E-05	-7,11E-07	-8,30E-09

***Tab 2** – Force factors in the Non Linear model*

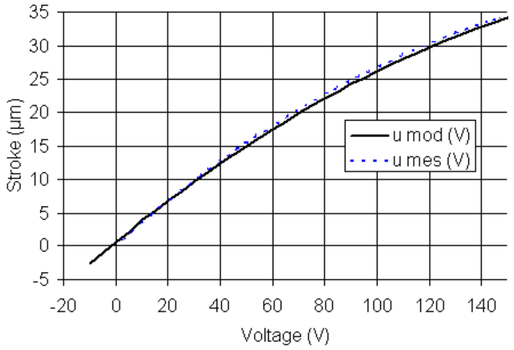

***Fig 7** : Measured stroke (u mes) of the APA30uXS compared to the non linear model (u mod).*

Conclusion

The dynamic strains of an APA closed to the voltage and the force limits has been analyzed both theoretically and experimentally. Dynamic stroke 50% higher than stroke in static and resonant conditions are predicted and measured thank to the actuator high prestress. However some new limits arise at high level in forms of sub-harmonics of the main mode. These are investigated by a new non-linear model based on a series of force factors. This model seems to explain these sub-harmonics and to be correlated by the measured stroke-to-voltage actuator response, but required further investigations.

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