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Scaling of piezoelectric actuators: a comparison with traditional and other new technologies

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Miniaturization is not a logical trend in actuator systems. Unlike actuators, sensors intrinsically perform more efficiently upon miniaturization. This is a logical consequence of the exchange of energy in the transduction process when applying sensors: measurement ideally should not influence the system being measured, thus the minimum exchange of energy is necessary and this intrinsically leads to miniaturization. In actuators, a transduction process is likewise established but the aim is to impose a mechanical state on a system. It is of particular interest not having this state influenced by perturbations, thus there are strong requirements on power delivered by the actuator. In view of current trends towards miniaturization, it is worth inquiring how the performance of piezoelectric actuators is affected by reducing their size. We are not concerned here with the domain of micro-actuators, i.e. actuators with sizes in the micrometer range. The analysis in this paper focuses on studying how four useful parameters for describing the performance of actuators are influenced by miniaturization: resonance frequency, force density, response time (bandwidth), stroke and energy density per cycle. In so doing, the analysis is restricted to non resonant piezoelectric actuators, i.e. stack, multimorph and inchworm actuators, but reference to other piezoelectric, emerging and traditional actuators is included for comparison.

Keywords: scaling laws, piezoelectric stack actuators, inchworm actuators, multimorph actuators

Escalado de actuadores piezoléctricos: comparación con los tradicionales y otras nuevas tecnologías.

La miniaturización de los dispositivos actuadores no es una tendenca lógica de su naturaleza de operación. Al contrario que los actuadores, los sensores si presentan esta tendencia a la miniaturización fundamentada en la naturaleza de su operación: dado que en el proceso de medida el intercambio energético debe ser mínimo para no afectar el proceso de medida, cuanto menor sea el sensor menor será también su efecto sobre la medición. En el caso de los actuadores el objetivo es el opuesto, se pretende imponer el estado mecánico de un sistema y que este estado no sea perturbado por agentes externos de forma que los requisitos sobre la potencia del actuador son estrictos. En vista de la tendencia actual a la miniaturización de las aplicaciones, conviene preguntarse como se ven afectadas las características de operación de los actuadores cuando son miniaturizados. El análisis presentado en este trabajo se centra en determinar como evolucionan las características principales de los actuadores (frecuencia de resonancia, densidad de fuerza, tiempo de respuesta, máximo desplazamiento y densidad de energía por ciclo) al ser miniaturizados. El análisis se restringe a actuadores piezoelectricos no resonantes, en concreto multicapa, multimorfos y cíclicos, pero se ponen en contexto con otros actuadores piezoeléctricos, con otras tecnologías emergentes y con tecnologías tradicionales.

Palabras clave: leyes de escalado, actuadores multicapa, actuadores cíclicos, actuadores multimorfos.

1. INTRODUCTION

Sensors and actuators are specific instances of tranducers. The ultimate goal both in actuators and sensors is to establish a energy conversion process. In the case of sensors, i.e. direct piezoelectric effect, the energy conversion is from mechanical work to electrical energy. Since the sensing process is to be conducted ideally without influencing the variable being measured, this exchange of energy must be kept to a minimum, see Busch-Visniac, (1). In this regard, miniaturization is a logical trend when dealing with senosrs.

However, this is not the case for actuators. Actuators also transform energy between different domains, chiefly between electrical and mechanical ones. Actuators are used to impose the mechanical state of a plant and thus ideally they should not be influenced by the load. This implicitly requires the need for high energy and/or power conversion and miniaturization is not a logical trend. Current application and technological trends towards miniaturization impose strict requirements on actuators. Actuators are intrinsically high power devices. The higher the power they can deliver, the more optimal their performance is.

Higher power availability is an indication for instance of higher frequency bandwidth or higher rejection of load disturbances. Miniaturization does not therefore logically lead to optimization of actuator performance. Rather, miniaturization of actuators must be seen as an application requirement.

Electroceramic actuators encompass a wide variety of devices exploiting either electrostriction or piezoelectricity in ceramic materials. Most of the implementations, both at research and industrial levels, are based rather on piezoelectric ceramics. Piezoelectric actuators can further be classified into resonant and non-resonant type actuators, see (2). On the one hand, the most known instance of resonant type piezoelectric actuators are the so-called travelling wave ultrasonic motors.

On the other hand, three are the principal non-resonant piezoelectric actuators, namely, stack piezoelectric actuators, multimorph actuators and inchworm actuators.

In view of the current trends in application towards miniaturization and the high power requirements of actuators, it is worth exploring how actuators' performance indicators evolve upon scaling. The behavior of an actuator upon scaling is a characteristic of each technology and can be assessed by analyzing how the various different performance parameters (efficiency, power and work density, response time, force and stroke) evolve upon scaling.

The analysis of scaling of actuators is a complex task. The reader is referred to Madou, (3), Peirs, (4) or (5-7) for additional details on scaling. Here, we will give some theoretical background with experimental examples where possible. The paper comprises three sections. In the first section, a few concepts on scaling are introduced. The next section develops scaling laws for piezoelectric actuators. The third section discuss the experimental validation of the theoretical prediction of previous sections and puts piezoelectric actuators in context by analyzing them comparatively to other types of emerging actuator technologies (magnetostrictive…)

2. SCALING LAWS

In order to analyze how the performance of actuators evolve upon scaling, a dimensional analysis of performance indicators must be conducted. This dimensional analysis correlates performance indicators, i.e. force, stroke, bandwidth, energy conversion, power… with the dimensions of the actuator.

In this paper we will restrict our scaling analysis to actuators based on direct transducing configurations, in which the trasducing phenomena are directly applied to obtain a displacement. This is the case of piezoelectric stacks in which a displacement proportional to the stack length and applied electrical field is used, for instance, for submicrometer positioning. As opposed to direct transducing, geometrical actuators are those in which the energy conversion is based on the exploitation of some geometrical configuration. This is for instance the case of electromagnetic actuators, see figure 1, where the geometry of the magnetic flux with regard to the configuration of the current flowing in the coils leads to Lorentz interaction, which, in turn, results in rotational motion of the coil.

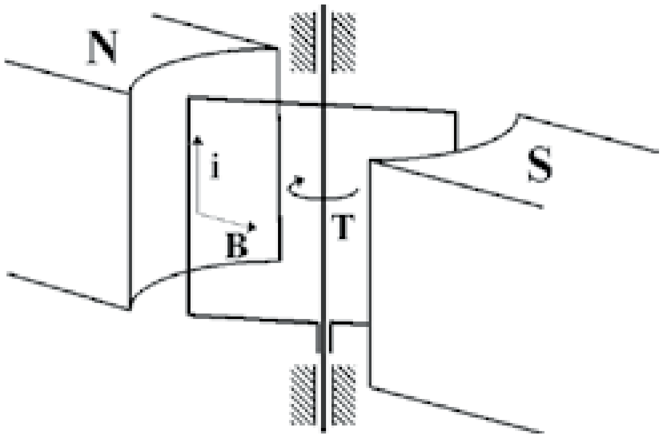

Fig. 1- An example of geometrical actuator: the electromagnetic DC drive exploits Lorentz interaction between a magnetic field and a flowing electrical current to obtain a torque on the coil.

For direct transducing configurations (piezoelectric stacks, multimorph or inchworm actuators), finding the available force, stroke and work density upon scaling is not a difficult task. We start by letting L denote the dominant dimension of the actuator. If this is true, the cross sectional area, A, of such an actuator is proportional to L squared, $A \propto L^2$. Likewise, the overall volume of the actuator is proportional to the third power of L, $V \propto L^3$. It is implicitly assumed in this scaling analysis that all the dimensions of the actuators are scaled proportionally.

In this analysis we will consider the volume of the actuator as the volume of the piezoelectric material. This is approximately the situation for piezoelectric ceramic actuators, where the establishment of the electrical potential to drive the actuator only requires printed electodes on opposite faces of the actuator and external electrical/electronic drivers. If we were to analyze magnetostrictive actuators, the requirements of external coils to set up the magnetic field most likely would lead us to consider also the volume of the coils (which in general is not negligible) in the analysis.

Under this assumption, the overall density of the actuator can be considered constant upon scaling, i.e. $\rho \propto L^0$. As a consequence, we can consider that also the mass of the actuator, M, remains proportional to the volume upon scaling and thus, $M \propto L^3$.

Force upon scaling. When analyzing the available force of an actuator, the relevant dimension, L, for most technologies (e.g. piezoelectric actuators, Shape Memory Alloy actuators, Magnetostrictive actuators and most Electro-Active actuators) is the dimension of the cross section. This means that the force is proportional to the cross sectional area of the actuator. The force, F, is then easily found following the scaling law of the next equation. In this discussion it is implicitly assumed that material characteristics will remain roughly invariant upon miniaturization. In this regard, it is clear that available force will be restricted by the material's yield stress, but we are rather interested in the behaviour upon miniaturization irrespective of material limitations.

$$F \propto L^2 \qquad [1]$$

Upon scaling the dominant dimension, L, the available force scales as L^2. Dimensions multiplied by 10 lead to available force multiplied by 100. The opposite occurs when scaling down the actuator's dimensions, when the actuator is miniaturized by a factor of 10, the actuator's force should be rougly reduced by a factor of 100.

Stroke upon scaling. In this case, the stroke, D, of the actuator is usually given as a percentage of its length, i.e. in piezoelectric stack actuators, the maximum static stroke is in the order of 0.1-0.15 %. Thus, the dominant dimension is the length of the actuator, L, see figure 2a. In the case of multimorph actuators, the available stroke is the transversal dispacement due to bending, in this case the dominant dimension to define stroke is the multimorph length, L, see figure 2b. The stroke scales linearly with the scaling of the actuator:

$$D \propto L \qquad [2]$$

When the dimensions of the actuator are multiplied or

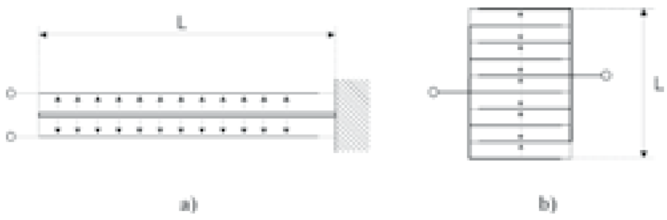

Fig. 2- Dominant dimensions for stroke upon scaling: a) the free length of the multimorph actuator and b) the length of the stack piezoelectric actuator.

divided by 10, so is the stroke.

Work density and Specific work density upon scaling. An upper bound to work can be readily determined as the product of the maximum displacement and force, $W_m = F \cdot D$. In addition, as previously discussed, the volume of an actuator obeys a scaling law proportional to the third power of the dominant dimension, $V \propto L^3$. It follows, then, that the work density, defined as the ratio of work to volume, scales according to the following expression:

$$W_{\mathrm{V}} \propto \frac{L^2 \cdot L}{L^3} \propto L^0 \quad [3]$$

The above equation indicates that, for most actuator technologies, the available work density per cycle remains roughly constant upon scaling.

When considering the effect of scaling on dynamic properties (power density, time constant, frequency) the analysis becomes more complex. This entails identifying what particular factors will become dominant upon scaling, so that they effectively limit the dynamic performance of the actuator. Once the dominant factor is identified, its evolution upon scaling is estimated.

In particular, the time constant of the actuator (which can be used to work out all the other dynamic properties from the static ones) may be limited by a variety of factors for a single actuator technology. In the case of piezoelectric actuators in particular, the time constant (which gives an indication of the maximum attainable frequency) can be limited by:

1. the resonance frequency of the actuator, which in most cases imposes the driving bandwidth. Typically, non-resonant actuators are driven at frequencies well below the first resonant frequency of the actuator, therefore, the value of the first resonant frequency is one of the upper bounds to the driving frequency.

2. the heating of the piezoelectric ceramic, which can lead to depolarization if the Curie temperature is reached, and

3. the charging time of the capacitor.

In other actuator technologies, the limiting factors for the time response may be very different: heat dissipation (conduction or convection) in thermal actuators; mass transport or diffusion in Ionic type Electro-Active Polymers or Shape Memory Actuators.

3. SCALING OF PIEZOELECTRIC ACTUATORS

In view of current trends towards miniaturization, it is worth inquiring how the performance of piezoelectric actuators is affected by reducing their size. We are not concerned here with the domain of micro-actuators, i.e. actuators with sizes in the micrometer range for which other fenomena might arise.

In addition to the intrinsic change of driving characteristics directly related to the actuator, the influence of changes in physical phenomena may be relevant in the domain of micro-actuators. This is true of surface forces that become dominant as compared to volume forces when the application is scaled down to this domain. For a detailed discussion on scaling laws, the reader is referred to works by Madou and Peirs, (1) and (2) respectively.

It has been reported, (1), that the piezoelectric effect scales down with the size of the actuators but this is not expected to have a measurable impact on a microscopic scale. The analysis in this section focuses on four useful parameters for describing the performance of actuators:

Resonance frequency. Resonance frequency is a very important parameter in describing the performance of piezoelectric drives, irrespective of whether they are resonant or non-resonant drives. In resonant drives, it is the resonance frequency that is used to drive the actuators; this is closely related to the speed of the linear or rotative motion and defines the characteristics of the electronic driver to a great extent.

In non-resonant drives, on the other hand, the resonance frequency is usually one of the upper limits for the feasible driving frequency.

Stroke. The stroke is an important parameter in the case of non-frictional transmission of displacement: e.g. in piezoelectric stacks and multimorph benders. In the case of frictional transmission of displacement, e.g. linear or rotational ultrasonic motors and inchworm motors, the stroke is either unlimited or it is only limited by the rotor length. Stroke was defined in the previous section for all actuator technologies and will not be dealt with in more detail here.

Force density. The force density describes the ratio of available force to volume or weight of the actuator. It is useful because it is closely related to the time response of the actuator.

Power density. The power density can be obtained from the previous parameters. It is defined as the ratio of available power to volume or weight.

3.1 Resonance frequency

Manufacturers of piezoelectric drives usually give the following relationship between the resonance frequency of the actuator and the size:

$$f_{\mathrm{r}} = \frac{N}{L} \quad [4]$$

where f_r is the resonance frequency of the piezoelectric ceramic, N is an actuator-specific constant dependent on the vibration mode of the particular ceramic (e.g. longitudinal for stacks, flexure for multimorphs) and L is the actuator's length in the direction of the vibration mode (e.g. length for stacks, thickness for multimorphs).

According to equation [4], all types of piezoelectric drives should exhibit the same tendency for the resonance frequency to increase at a rate inversely proportional to the decrease in size. Figure 3 shows the evolution of the resonance frequency of piezoelectric stack actuators from various different manufacturers.

As the figure shows, the overall trend in piezoelectric stacks conforms to equation [4]. This result is also consistent with the scaling analysis of Peirs, (2). According to this analysis, the stiffness of second order mechanical systems scales down linearly with the size of the actuator: i.e. $K \propto L$. Since the mass of the actuator will scale down according to the volume of the actuator (i.e. $M \propto L^3$), the resonance frequency of the actuator (which is a second order mechanical system) is:

$$f_r \propto \sqrt{\frac{K}{M}} \propto L^{-1} \quad [5]$$

The result of figure 3 confirms the resonance frequency trend described by equations [4] and [5]; it also indicates that the bandwidth of non-resonant drives and that the driving frequency of resonant drives will increase upon miniaturization.

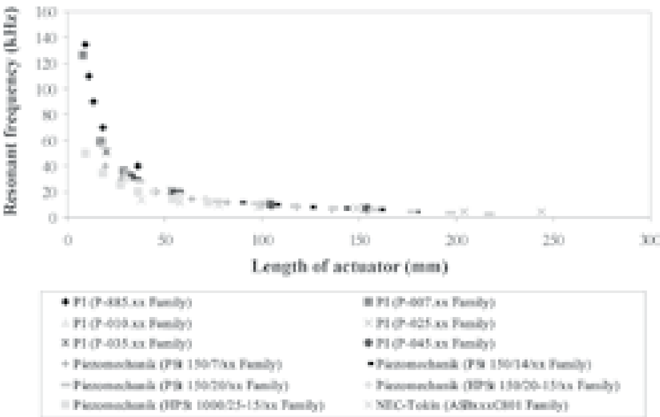

Fig. 3- Experimental verification of scaling trends for the first resonant frequency (as an upper bound to maximum driving frequency) of piezoelectric stack actuators. Data obtained from datesheets of principal manufacturers. The data show an inversely linear relationship between resonant frequency and size (length of the actuator).

3.2 Force density

Force density is defined here as the ratio of available force to volume. Force density is closely related to the acceleration that the actuator is able to impart to the load and also to the response time of the system.

Since the mass, M, and the volume, V, of the actuators are proportional, the force density is also proportional to the acceleration, a, of the load:

$$M \propto V \propto L^3 \quad \Rightarrow \quad \frac{F}{V} \propto a \quad [6]$$

The experimental relationship between force density and volume is depicted graphically in figure 4. It will be seen that the force density in piezoelectric actuators is inversely proportional to the length in the direction of the displacement. This again confirms the theoretical result of Peirs, (2), who established the following relationship:

$$\frac{F}{M} \propto \frac{F}{V} \propto \frac{1}{L} \quad [7]$$

where L is the dominant dimension in the actuation displacement.

The result of equation [7], experimentally verified in figure 4, shows that the force density of piezoelectric stack actuators is inversely proportional to the dimensions of the actuator. This is closely related to the level of acceleration attainable with the actuator, i.e. small actuators are intrinsically faster

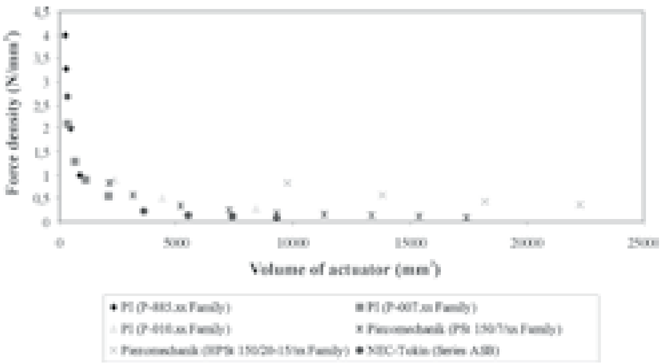

Fig. 4- Experimental verification of scaling trends for the force density (as an upper bound to maximum acceleration) of piezoelectric stack actuators. Data obtained from datesheets of principal manufacturers. The data show an inversely linear relationship between force density and size (length of the actuator).

and the degree by which they become faster is qualitatively according to equation [7].

3.3 Response time

A similar analysis can be used to establish the trends in response time of the piezoelectric actuators upon miniaturization. It is clear from equation [6] and [7] that the response time tends to decrease linearly upon miniaturization:

$$a \propto \frac{1}{L} \propto \frac{L}{T^2} \quad \Rightarrow \quad T \propto L \quad [8]$$

This analysis takes only the mechanical characteristics of the active material into account. In the derivation, the volume of the electronic drive was not taken into consideration, so that they indicate trends rather that the exact situation.

This can be seen again in the case of the response time. As explained earlier, one of the factors limiting the response time derives from the charging and discharging time of the capacitor that piezoelectric actuators represent when driven out of resonance. The electrical capacitance of the piezoelectric actuator, C_p, is proportional to the capacitor area, A, and inversely proportional to the distance between electrodes, L. The tendency of the electrical capacitance would be to decrease linearly when the actuator is miniaturized:

$$C_p \propto \frac{A}{L} \propto L \quad [9]$$

This will produce an effect on the response time in addition to the effect discussed in the foregoing paragraphs.

The result in this section is coherent with the previous result on the effect of scaling on frequency. It is well know that in linear systems, the time constat of a filter is inversely proportional to its cut off frequency. An actuator is a second order linear system and its response can be regarded as a filter. By means of this analogy, the time response of the actuator and the cut off frequency follow an inversely proportional relation, which is verified by equations [5] and [8].

4. EXPERIMENTAL VALIDATION AND DISCUSSION

Most of the results and scaling laws as presented in the previous section are general and applicable to traditional (pneumatic, hydraulic, electromagnetic) as well as to new and emerging (piezoelectric, magnetostrictive, electroactive polymers) actuators. As previously mentioned, the most significant difference amongst the various technologies is in their dynamic performance indicators.

It is therefore appropriate to put piezoelectric actuators in context with other actuator technologies. In this section, the experimental verification of scaling laws for force density, stroke, energy density per cycle, power density and bandwidth is shown for piezoelectric actuators, in particular for stack actuators, multimorph actuators, inchworm actuators as well as for travelling wave ultrasonic motors, both linear and rotational. In addition, also other technologies are considered in the experimental analysis. The purpose is rather showing the relative position of piezoelectric actuators as compared to other technologies than showing scaling treds for these technologies.

4.1. Scaling law and relative position in terms of force density

Force density has been defined as the ratio of maximum available force to actuator volume or weight. This figure of merit applies to linear actuators , therefore only stacks, inchworms and multimorphs are considered.

The chart in figure 5 plots force density versus size for all the relevant emerging actuators and for linear electromagnetic motors and pneumatic actuators for comparative purposes. Since the force density is plotted versus the actuator's size, it can be used to check scaling trends.

The theoretical scaling analysis for force density shows an inverse linear relationship with actuator dimensions ($F_V \propto L^{-1}$ N/cm^3). Lines showing this theoretical trend have been plotted on the graph. The graph shows several interesting features:

1. Traditional technologies (electromagnetic DC motors and pneumatic actuators) can only be found in sizes higher than approximately 100 cm^3, while piezoelectric linear actuators are mainly located in the area of sizes below 100 cm^3 and thus complement each other.

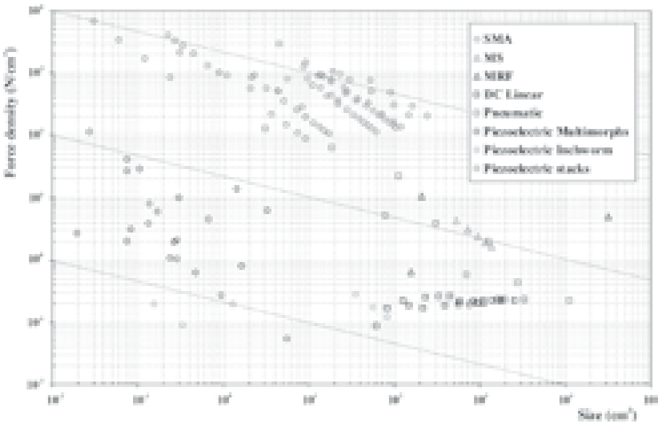

Fig. 5- Experimental verification of scaling trends for the force density as well as relative position of traditional and emerging actuator technologies. Data obtained from datasheets from commercial actuators.

2. The experimental data obtained from commercial datasheets confirms the theoretical predictions in terms of force density. This can be considered demonstrated for both stack and multimorph piezoelectric actuators, for which the number of samples in the chart are representative.

3. The other emerging technologies (magnetostrictive actuators, Shape memory actuators and magneto-rheological actuators) show overlaping with piezoelectric actuators to some extent.

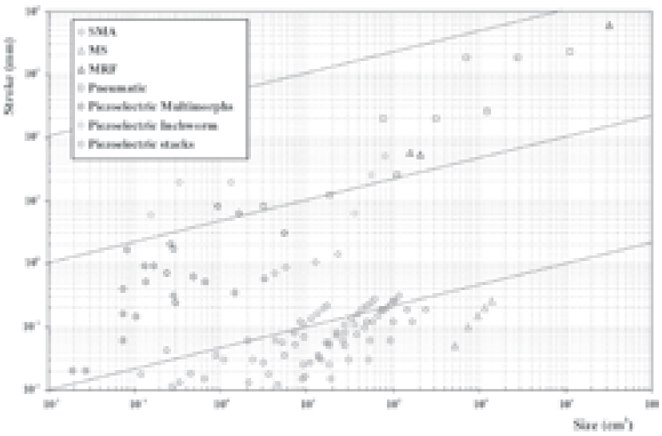

Fig. 6- Experimental verification of scaling trends for the stroke as well as relative position of traditional and emerging actuator technologies. Data obtained from datasheets from commercial actuators.

4.2. Scaling laws and comparative analysis in terms of stroke.

The stroke has been defined as the maximum available displacement for an actuator. This figure of merit applies to the same set of actuator technologies as the two previous cases. In emerging actuators, the stroke is typically determined as a fraction of the actuator's length. The following may be said about the stroke of piezoelectric actuators:

1. Piezoelectric stack actuators. These have the lowest stroke of all actuator technologies. In practice it is limited to about 0.1-0.15% of the actuator's length for static applications. As figure 6 shows, the stroke of these actuators is relatively low compared to any of the other technologies.

2. Piezoelectric multimorph actuators. These have a higher stroke than stacked actuators or Magnetostrictive actuators. Their stroke levels are moderate (see figure 6).

3. Piezoelectric inchworm actuators. These deliver the highest stroke of all piezoelectric technologies, similar to MRF actuators, and may be considered moderate to high.

Figure 6 shows a chart depicting the relationship between stroke and size in various different commercial implementations of all emerging actuator technologies with special focus on piezoelectric actuators. It can be used to analyze the scaling trend of stroke for these technologies (which is $D \propto L$). The lines describing the theoretical trend are included to assist such analysis.

The figure also shows how piezoelectric and traditional actuators are clearly positioned in different size and stroke areas. Piezoelectric actuators are small as compared to traditional ones and give rise to low strokes (down to micrometric and nanometric displacements) as compared to traditional ones. Only magnetostrictive actuators fall in the same stroke area as piezoelectric actuators.

4.3. Scaling laws and comparative analysis in terms of work density per cycle.

Work density per cycle is one of the dynamic figures of merit described and analyzed in previous sections. It is the ratio of the maximum work per cycle to the size or weight of the actuator. The relative positions of the different actuator technologies for this figure of merit are represented graphically in figure 7. The scaling trend for the work density per cycle indicates a roughly constant energy density per cycle upon scaling ($W_V \propto L^0$). This feature can be readily verified by looking at the evolution of the various technologies for different actuator sizes, in particular to the evolution of piezoelectric stack and multimorph actuators.

Figure 7 also includes data on resonant type piezoelectric motors, in particular Travelling wave ultrasonic motors, both rotational and linear. All piezoelectric actuators are clustered as low work density and low size devices and thus again complement the features of other actuator technologies. It is maybe the scaling properties of work density the one that can be better validated in view of figure 7 for all actuator technologies. Data in figure 7 has been obtained from datasheets of commercial actuators. Whenever the available energy density was not quoted as one of the performance parameters, the assumption was made that the maximum energy per cycle for an actuator (piezoelectric and magnetostrictive) corresponds to the maximum potential energy and thus it was worked out of the maximum stroke and the stiffness of he actuator.

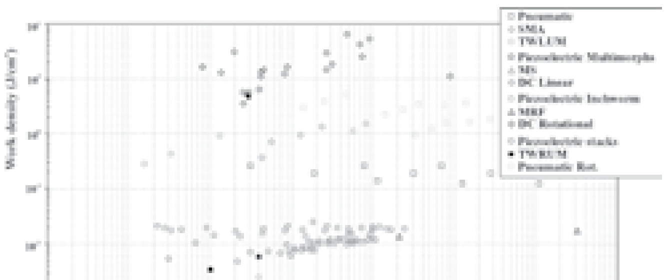

Fig. 7- Experimental verification of scaling trends for the work density as well as relative position of traditional and emerging actuator technologies. Data obtained from datasheets from commercial actuators

4.4. Scaling laws and comparative analysis in terms of power density

Power density has been defined as the ratio of maximum output power to the volume or weight of the actuator. It is analyzed in this section for piezoelectric actuators as well as for all the other traditional and emerging actuator technologies.

Power density is high only for Piezoelectric stacked actuators. It may be considered moderate for Piezoelectric Multimorph actuators, Pneumatic linear and rotational actuators, Electromagnetic linear and rotational motors, Travelling Wave Linear and Rotational Ultrasonic motors (TWLUM and TWRUM) and Magnetostrictive actuators. It is low for Shape Memory Alloy actuators and Piezoelectric inchworm actuators.

According to the scaling analysis for most technologies, the power density scales between $P_V \propto L^{-1}$ and $P_V \propto L^{-2}$. Figure 8 shows trend lines for these theoretical result to give an idea of the accuracy of this prediction. The experimental data fit the theoretical result well enough, the number of data points for piezoelectric actuators is representative although the number of specimens for other technologies should be higher for conclusive results.

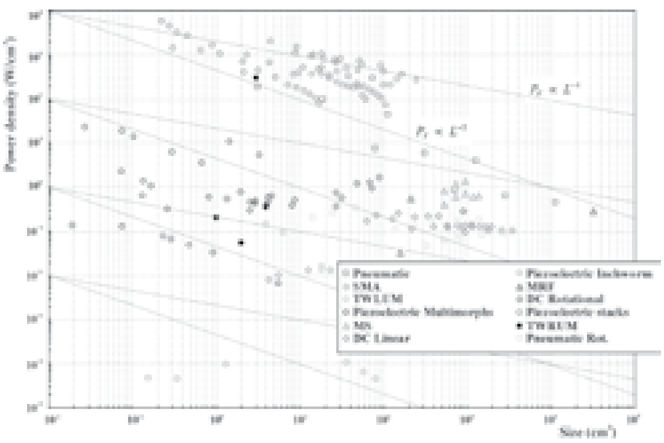

Fig. 8- Experimental verification of scaling trends for the power density as well as relative position of traditional and emerging actuator technologies. Data obtained from datasheets from commercial actuators

4.5. Scaling and comparative analysis in terms of bandwidth.

This section presents a comparison of the different emerging actuators in terms of the maximum actuation frequency they can withstand. The theoretical scaling laws

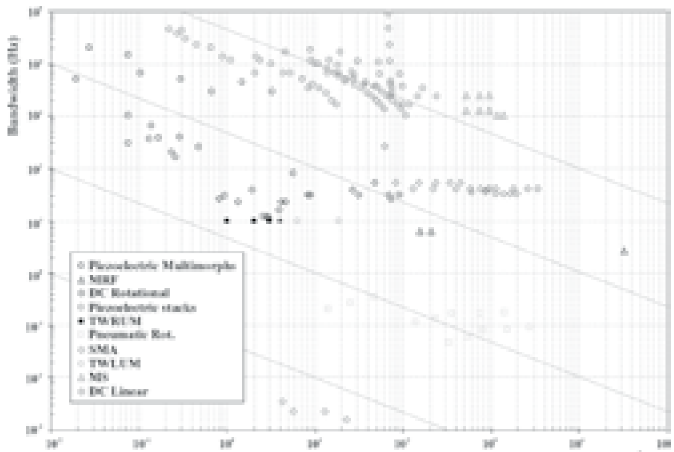

Fig. 9- Experimental verification of scaling trends for the bandwidth as well as relative position of traditional and emerging actuator technologies. Data obtained from datasheets from commerci

for the actuator's bandwidth vary between $f_r \propto L^{-1}$ and $f_r \propto L^{-2}$. The corresponding trend lines are indicated in figure 9. In general, the smaller the actuator, the higher is the frequency bandwidth.

The chart in figure 9 shows bandwidth versus size for all emerging actuator technologies, and also for Electromagnetic and Pneumatic linear and rotational drives.

Piezoelectric stack and Multimorph actuators and Magnetostrictive actuators may both be considered fast technologies. At the opposite extreme, Pneumatic rotative actuators and SMAs are slow actuators. All the other technologies, i.e. linear and rotational Electromagnetic motors, Travelling Wave Linear and Rotational Ultrasonic motors and Magneto-Rheological actuators have moderate bandwidth.

5. CONCLUSION

This paper introduces a qualitative analysis of scaling trends for piezoelectric actuators. The scaling analysis is based on the assumption that scaling does not affect significantly the piezoelectric and physical properties of the piezoelectric material on which the actuators are based.

Most of the scaling laws developed in this paper are common to other actuator technologies, both traditional (electromagnetic, pneumatic, hidraulic) and based on new (or newly developed) transducing phenomena. As such, the scaling analysis presented here allows a comparative analysis of the various different technologies in terms of several performance indicators.

The main results indicate that the available mechanical energy density per cycle for piezoelectric actuators remains roughly constant upon scaling. The resonance frequency, force density and the power density of the actuators (which can be considered as second order linear systems) scale in inverse proportion to its size. These results have been qualitatively validated with experimental data from datasheets of commercial actuators. The comparative analysis of technologies indicated complementary performance between traditional and new actuators but overlapping to some extent amongst new technologies, in particular between piezoelectric and magnetostrictive actuators.

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