Combined Finite Element Analysis – Genetic Algorithm Method for the Design of Ultrasonic Motors

PHILIPPE BOUCHILLOUX[1,*] AND KENJI UCHINO[2]

[1]*Adaptronics, Inc., 1223 Peoples Ave., Troy, NY, USA*

[2]*The Pennsylvania State University, 134 Materials Research Laboratory, University Park, PA 16802, USA*

ABSTRACT: The operation of a linear or rotary ultrasonic motor relies on the production of an elliptical vibration at the surface of the stator. To achieve a suitable vibration state, many ultrasonic motors use a combination of structural modes of the stator. Because these modes may be different in nature, designing a viable stator is not trivial. In addition, the design may be complicated by other considerations, such as the electromechanical coupling coefficient of the piezoelectric elements, the amplitude of the vibrations, and the force factor of the device. Similarly, it may also be desired to incorporate parameters such as the operation frequency, geometrical dimensions and weight, electrical current and so on, which may render the design problem extremely difficult to solve.

To help in designing such ultrasonic structures, it is proposed to use the genetic optimization method in combination with the finite element method. The combination of these two design tools is innovative and provides a unique approach to the complex problem of ultrasonic motor design. In this paper, the general aspects of the method utilized are reviewed and an application example that includes experimental verification data is provided.

Key Words: piezoelectric ultrasonic motor, finite element analysis, genetic algorithm, optimization

INTRODUCTION

THERE has been a notable increase of interest in ultrasonic motors in the U.S. in the past few years. These ultrasonic devices are quickly spreading in various sectors of the industry, and in particular, in aerospace (Lih et al., 1997) and optics (Zhang and Zhu, 1997). The reasons are primarily that these motors have little, if any, magnetic interaction with their environment; they are compact and light, have low energy consumption, and display larger torque to weight ratios than their electromagnetic counterparts. In addition, ultrasonic motors usually operate at low speeds so that gears and similar speed-reducing components are not necessary. Finally, due to large holding torques, ultrasonic motors have the capability of maintaining their position when the power is turned off.

Many of these ultrasonic motors (Ueha and Tomikawa, 1993; Uchino, 1997) use a combination of structural modes to generate the desired elliptical vibration field that ultimately results in the linear or rotary motion of an object. Designing an ultrasonic device that combines structural modes of vibration is not trivial, especially when performance criteria, such as the electromechanical coupling coefficient of the piezoelectric elements, the amplitude of the vibration, and the force factor of the device are to be maximized. Other parameters may also be combined and render the design task even more difficult: targeting a specific frequency, constraining dimensions, adding electrical considerations, etc.

PRESENTATION OF THE METHOD

To successfully design an ultrasonic motor, it is often necessary to simultaneously determine a large number of parameters. This is particularly true with mixed-mode ultrasonic motors (MMUM), because they combine at least two structural modes of vibration of different natures, i.e., modes that respond differently to the geometry and mechanical properties of the device. Typically, these normal modes must display similar frequencies, such that the vibrations resulting from each one can be effectively combined in an elliptical field. Additionally, because these modes are excited by means of piezoelectric elements, maximizing the electromechanical coupling for each mode, and consequently the force factor of the ultrasonic device, is of great importance (Le Letty et al, 1995, 1997). Finally, the amplitude of the vibration must be evaluated in order to

*Author to whom correspondence should be addressed.
E-mail: pb@adaptronics.com

1045-389X/03/10 0657–11 $10.00/0 DOI: 10.1177/104538903038105

determine the viability of the system, as too small vibration amplitudes would not allow the rotor to move.

This list of parameters is clearly not exhaustive. The complete analysis of the ultrasonic motor requires further analysis of the tribology of the contact mechanism at the stator–rotor interface, for instance. However, at this stage of our work, most efforts are focused on the stator (or vibrating element) of the ultrasonic motor alone. The method presented here allows for including higher levels of complexity in the system, and it will eventually be extended to include complete ultrasonic motor analysis and optimization capabilities.

The proposed method combines the genetic algorithm with finite element analysis. The finite element analysis (FEA) method has proven to be applicable to the modeling of a large variety of structures. Commercial FEA software, such as ATILA (ATILA), specializes in the analysis of smart structures and is efficient at solving a variety of piezoelectric structures (Bouchilloux et al., 1997; Koc, 2000). For this reason, ATILA was chosen as the numerical analysis tool to evaluate the quality of ultrasonic stator designs.

The genetic algorithm (GA) was chosen among other optimization procedures for its multidimensionality and ease of implementation. The GA was also attractive for its capability of avoiding local optima and for rapidly finding the global optimum in the searched domain.

The basic principles of GA were first proposed by Holland (1975) and were inspired by the mechanism of natural selection where stronger individuals are the likely winners in a competing environment.

Genetic algorithms presume that the potential solution of any problem is an individual and can be represented by a set of parameters. These parameters are regarded as the "genes" of a "chromosome," which is a representation of the individual (Figure 1). The chromosome can be structured and is often represented by a string of values in binary form. To evaluate the individual, an objective function processes the

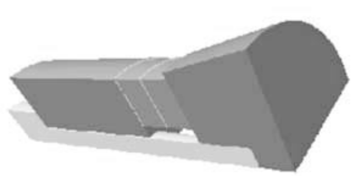
Genetic algorthim terminology	Example	Description and comments
Genes	$P_1, P_2, \ldots, P_M$	Design parameters
Alleles	P_1 0, 1, 2, ..., 7 P_2 0, 1, 2, ..., 31 ⋮ ⋮ P_M 0, 1, 2, ...	Values taken by the parameters (length, thickness, radius, etc.)
	Binary representation 0 1 0 = P_1 = 2 0 0 1 1 0 = P_2 = 6 ⋮ ⋮ ⋮ 0 1 ··· 0 1 = P_M	
Chromosome or individual	A Tonpilz transducer	A solution described by the design parameters
Genotype	P_1 P_2 P_M 0 1 0 | 0 0 1 1 0 | ··· | 0 1 ··· 0 1	A binary string
Phenotype		A possible design

Figure 1. *Brief glossary of genetic algorithms terminology.*

chromosome string. Within the context of this work, the evaluation function is a FEA of the individual. The result of this analysis is converted to an objective value, which is assigned to the individual and represents the performance of that individual against the objective function. Finally, a positive value, generally known as a "fitness" value, is used to reflect the degree of "fitness" of that particular individual within the population. The fitness value can be "raw" (absolute), or relative, thus allowing individuals to be sorted from strongest to weakest. Attributing fitness values permit later operations, such as selection and reproduction, to be performed. Clearly, the fitness value is closely related to the objective value and reflects how well an individual performs.

Throughout a genetic evolution, the fitter chromosome has a tendency to yield good quality "offspring," which means a better solution to the problem. A "population" pool of chromosomes has to be installed, and these can be randomly set initially. In each cycle of the genetic operation a subsequent "generation" is created from the chromosomes in the current population. Typically, this step involves three operators, "selection," "crossover" and "mutation," to direct the population towards convergence at the global optimum. The selection operator attempts to apply pressure upon the population in a manner similar to that of natural selection found in biological systems. A "roulette wheel" model is often used to represent this process, although this is not the most sophisticated method actually employed in GAs. In this process, each individual is assigned a section of the roulette wheel, the size of which is proportional to the individual's fitness value. Consequently, fitter individuals occupy larger sections of the wheel and have more chances of being selected (and surviving) each time the wheel is spun. Conversely, individuals with low fitness values are statistically less likely to be selected by the roulette wheel. These poorer performing individuals are weeded out while better performing, or fitter, individuals have a greater than average chance of promoting the information they contain within the next generation.

The crossover operator allows solutions to exchange information in a way similar to that used by a natural organism (Figure 2). The method consists of choosing pairs of individuals promoted by the selection operator, randomly selecting one or more points within the binary strings, and swapping the information (bits) from one point to another between the two individuals. The mutation operator (Figure 3) is used to randomly change the value of single bits within individual strings. Excessive use of this operator may disrupt the evolution process.

The application of GA to ultrasonic devices presents some difficulties. One of them concerns the coding of the genes, which may not always be regularly spaced integer numbers. For instance, design parameters usually correspond to the dimensions of the device. Eventually, these dimensions will be machined using traditional machine-shop techniques, and will be subject to constraints such as the size availability of the raw materials and the tolerance limits of the machining equipment. Therefore, most problems require that design parameters be real numbers, and often, discrete values. Discrete values can easily be mapped into a lookup table that the algorithm can consult to code and decode the corresponding gene. A simple and efficient solution for real values consists of considering a tolerance on the parameter value. For instance, if one parameter is used to represent the geometrical length of a section of the structure, and assuming that this parameter can take values between 10 and 20 mm, then it is usually sufficient to consider the real value with a tolerance of 0.01 mm for machining purposes. Therefore, scaling and shifting the alleles to map them with the integer values 0 to 1000 provides a satisfactory solution, where the integers 0, 1, and 1000 correspond to the real values, 10.00, 10.01, and 20.00 mm, respectively.

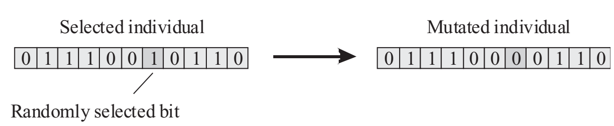


Figure 3. *The mutation operator causes an individual to change by one bit, randomly.*

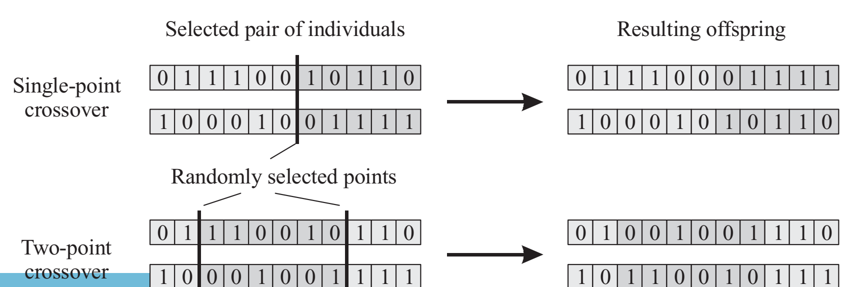


Figure 2. *The single- and two-crossover operators. Multiple point crossover operators are often preferred.*

Further, it is important to note that regular binary numbers may not be the most adequate to the genetic process. Indeed, note that the integers 7 and 8 are different by just 1, but their respective binary representations, 0111 and 1000, are different by 4 bits. To correct for this, Gray codes (Lee and Lee, 1999) are used instead of standard binary representations. Gray codes look much like binary codes in the sense that they display the same cardinality, and numbers are formed of 0s and 1s. However, unlike traditional binary, Gray codes allow a variation of just one bit between two successive integer values. Such canonical form is obtained by simply reordering the standard binary codes. For instance, integers 5, 6, 7, and 8 take the form 0101, 0110, 0111, and 1000 in binary form. They become 0111, 0101, 0100, and 1100 in Gray form. Only one bit is changed from one integer to the other.

A GA code following the general rules described above has been programmed in object-oriented Pascal on a PC platform. The complete algorithm is shown in Figure 4. The code was tested against more or less ill-behaved mathematical functions (Table 1), as it is classically done (Andre et al. 2001). These functions exhibit discontinuities, multiple optima, large dimensionality, and other characteristics that reveal potential weaknesses of the optimization algorithm. The latter should not be applied to real problems until it successfully passes all of these tests.

The connection between GA and FEA takes place as illustrated in Figure 5. The general flow diagram is similar to that of the GA itself, except for the evaluation function, which is now more complex and includes the FEA.

It is important to emphasize at this point that the evaluation function may include more than a single finite element run. Indeed, to evaluate the performance of the stator of an ultrasonic motor, it is required to determine, in general, the resonance frequency of each

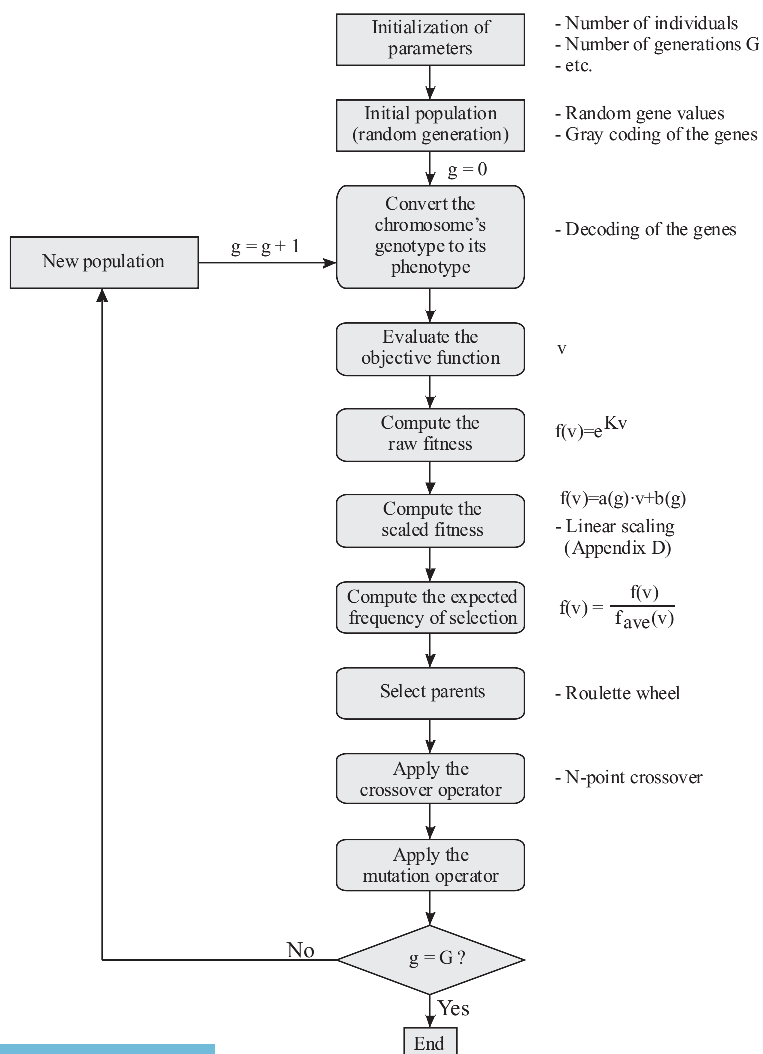


Figure 4. *General algorithm of the evolutionary process.*

participating mode, its electromechanical coupling factor, and the resulting motion produced at the contact interface. Usually, one or two modal analyses are required to determine the characteristics of the modes, and a harmonic analysis is necessary to determine the shape of the ellipse.

There is, therefore, more than one call to the finite element program (ATILA) for the evaluation of each individual. This increases the order of the algorithm rather significantly and may result in long computation times. To alleviate this problem, great care should be taken in minimizing the size and complexity of each finite element mesh. As a result, each finite element case may use a different mesh that enhances the computation time for that run.

Finally, the GA provides some advantages with respect to parallel computation. It is clear that the evaluation of each individual, for instance, can take place independent of the other individuals. Therefore, on a multiprocessor environment, it is possible to evaluate two or more individuals in parallel (Figure 6). This parallelization feature was incorporated in our program.

Table 1. Test-functions used to validate the optimization algorithm. The function INT(x) returns the nearest integer less than or equal to x. A is chosen to ensure a minimization problem.

Function	Limits
$F_1 = \sum_{j=1}^{3} x_j^2$	$-5.12 \le x_j \le 5.12$
$F_2 = 100(x_1^2 - x_2)^2 - (1 - x_1)^2$	$-2.048 \le x_j \le 2.048$
$F_3 = \sum_{j=1}^{5} \mathrm{INT}(x_j)$	$-5.12 \le x_j \le 5.12$
$F_4 = \dfrac{\sin^2\sqrt{x_1^2 + x_2^2} - 0.5}{(1 + 0.001(x_1^2 + x_2^2))^2}$	$-100 \le x_j \le 100$
$F_5 = A + \sum_{j=1}^{\le 30} [\mathrm{INT}(x_j + 0.5)]^2$	$-40 \le x_j \le 60$
$F_6 = A + 20\exp\left[-0.2\sqrt{\frac{1}{m}\sum_{j=1}^{m(\le 30)} x_j^2}\right] + \exp\left[\frac{1}{m}\sum_{j=1}^{m(\le 30)} x_j^2\cos(2\pi x_j)\right] + 20$	$-20 \le x_j \le 30$

The program that was developed to implement the technique presented above is rather general. The GA itself does not require modifications from one problem to another. Only the general settings (population size, gene size, probabilities of crossover and mutation) can be modified depending on the problem at hand.

The finite element mesh (or meshes) is, of course, problem dependent. However, using meta-functions (that were also developed) for the creation of the mesh makes it relatively easy to generate a mesh for any given problem, whether two- or three-dimensional.

Finally, the most sensitive part that must be modified for every problem is the function that evaluates the performance of each individual based on the finite element results obtained. Even for one given problem, this function may also depend on the type of result that is sought and thus require additional fine-tuning. At this time, this evaluation function can only be modified programmatically, although it could easily be extracted from the program and accessed from the user-interface. Usually, this evaluation function will contain terms associated with the operating frequency of the stator, the electromechanical coupling factor associated with each participating mode, and the

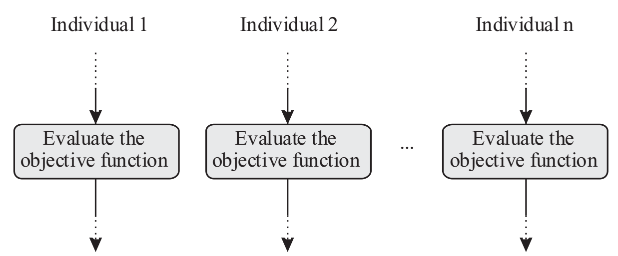


***Figure 6.** Parallel evaluation of individuals allows for speeding up the evolutionary process on a multiprocessor environment.*

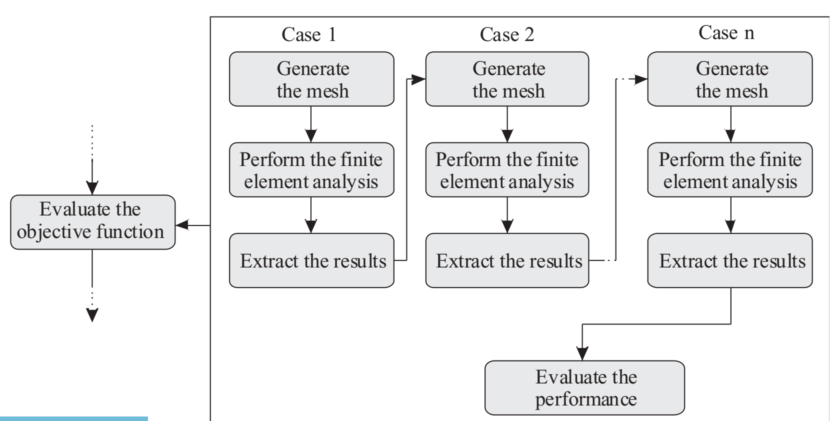


***Figure 5.** The combination of the FEA and GA methods takes place at the level of the evaluation function.*

elliptical factor associated with the vibration. Other terms, such as stresses, mass, volume, etc. can also be added. The selection of the terms that compose the evaluation function is mostly problem-dependent. One situation may require, for instance, that individuals exhibiting a low mass be privileged. The evaluation function could then include a term proportional to the individual's mass inverse. As a consequence, individuals with lower mass would receive a higher objective value, which would in turn indicate that these individuals are fitter.

APPLICATION EXAMPLE: MIXED-MODE ULTRASONIC MOTOR

The example that was chosen is that of a commercial mixed-mode ultrasonic motor manufactured by Cedrat Technologies, in France (Claeyssen et al., 1998; Le Letty, 1998). The schematic of the stator is shown in Figure 7. It includes two ceramic multilayer actuators, one center mass, and one elliptical shell.

The operating mode of the structure is shown in Figure 8. The modes of interest here are a flexure mode of the shell, which provides the normal component of the vibration at the contact interface, and a translation mode of the center mass, which provides the tangential component of the vibration (Figure 9). Note that the flexure mode is pure when both ceramic multilayer actuators are excited in phase, and that the translation mode is pure when both are excited in opposition of phase.

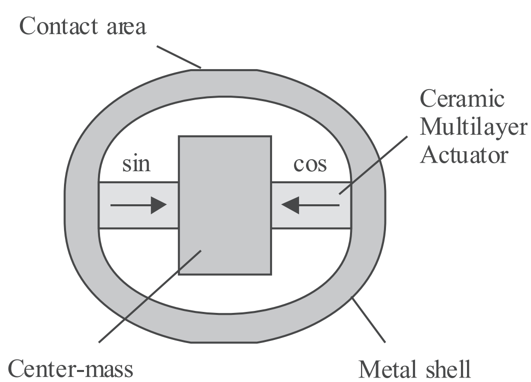


Figure 7. *Schematic of the multimode ultrasonic motor patented by Cedrat Technologies.*

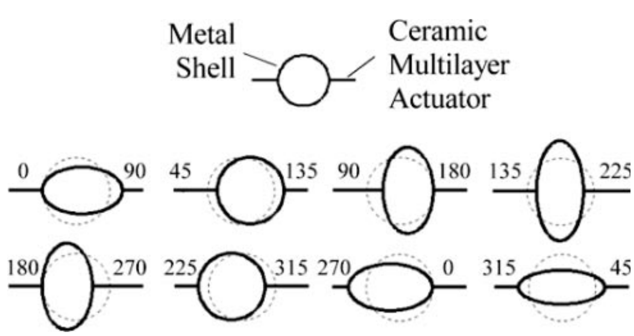


Figure 8. *Operating principle of the MMUM. The respective phase angles of each ceramic multilayer actuator is indicated on each drawing.*

One of the greatest advantages of such mixed-mode motors is that the two modes can be, within certain limits, controlled independently. Therefore, fine-tuning of the elliptical vibration field in the contact area can be performed and thus enables various operating modes of the motor to be defined.

The complete FEA of the stator is divided into three steps. First, two modal analyses are required to evaluate the frequency of the flexure and translation modes. Second, a harmonic analysis combining the two effects, with electrical signals in quadrature of phase, is used to determine the amplitude of the vibration as well as the ellipse factor. This procedure is summarized in Figure 10. The finite element meshes used for the modal analyses (Figure 11) minimize the computation time. They are two-dimensional and make use of the planes of symmetry and antisymmetry of the structure.

A total of six parameters have been identified from the general structure of the stator (Figure 12); these represent the genes of the individuals in the genetic procedure. These parameters consist of the thickness, inner and outer radii of the metal shell, and the length of the contact area, as well as the dimensions of the center mass. All parts are made of stainless steel. Since two-dimensional models are used and the out-of-plane dimensions are not the same for all the parts, equivalent

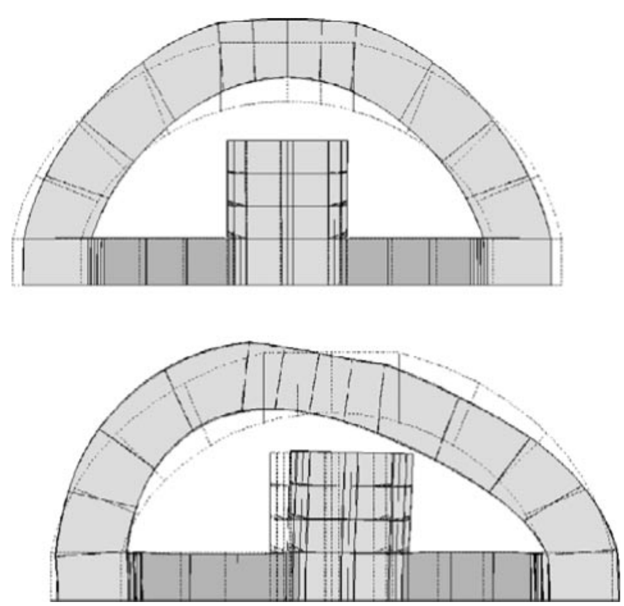


Figure 9. *Flexure (left) and tangential (right) vibration modes obtained by a detailed finite element analysis with ATILA.*

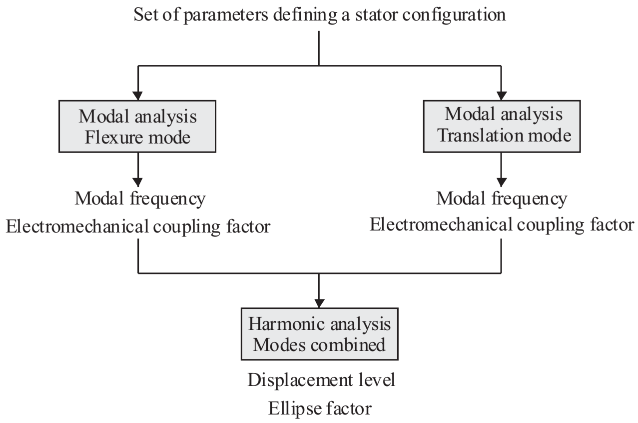


Figure 10. *The evaluation of each individual requires three finite element computations.*

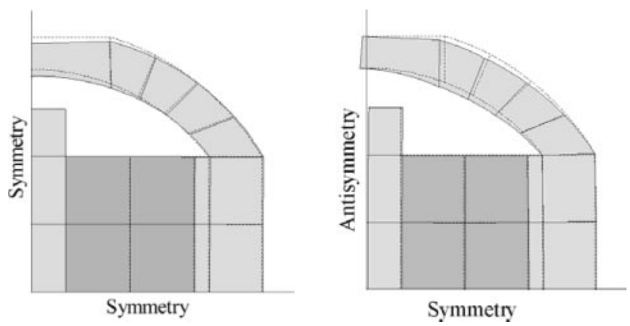


Figure 11. *Simplified finite element meshes used for the stator analysis during the optimization procedure. The model on the left is for the flexure mode; the one on the right is for the translation mode.*

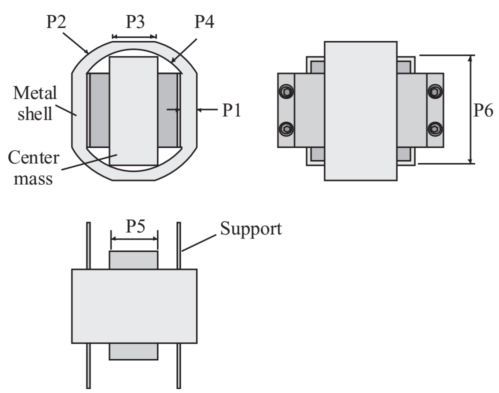


Figure 12. *Identification of the six design parameters used. The piezoelectric elements, as well as the support, are considered to have fixed dimensions.*

material properties are necessary, in particular for the center mass. The width of the metal shell is fixed to the width of the multilayer actuators, whose dimensions are considered to be fixed as well (they are 6.3 mm high and have a square cross section with sides of 12.7 mm). These actuators are composed of six plates of piezoelectric material poled in the thickness direction. In order to reduce the finite element model size, not all the layers are represented and equivalent material properties are used for the piezoelectric material as well.

Identification of the mode shapes indicate that there is no available nodal location on the structure. Therefore, affixing the stator to a mechanical reference is a task with antagonistic goals: on the one hand, the mechanical fixture must be sufficiently stiff to bear the stator weight and transmit the static pressing force between the stator and the rotor; on the other hand, these mechanical components must be sufficiently compliant so as to decouple the vibration of the stator from the mechanical support, thus limiting the amount of vibration energy that dissipates through them.

The supports, represented in Figure 12, are in fact simple metal plates. They are placed such that the contact interface is in a direction parallel to the plane of those plates, therefore allowing for large forces to be transmitted in that direction. On the other hand, these plates are relatively thin, so that they decouple the stator from the mechanical reference and thus avoid dispersing the vibration energy.

Because the supports operate in a different plane than that of the stator, and that it was decided to use two-dimensional models for the FEA, the supports were excluded from the optimization procedure and dimensioned by other methods.

The evaluation function for the performance of the individuals (defined by the values of the six parameters) is such that it favors:

- A total length (in the direction of the multilayer actuators) less than 1 in. (25.4 mm).
- An operating frequency as low as possible.
- An electromechanical coupling coefficient as high as possible for each mode.
- Vibration amplitudes as large as possible.
- An ellipse factor close to unity.

The objective function used in this problem is presented in Figure 13. The final performance, which combines all the criteria described in the previous section, is represented by a number between 0 and 1, 0 being the optimum value. In order to perform the mapping, it is useful to consider upper and lower bounds for each criterion. For instance, frequencies between 20 and 100 kHz are mapped to the interval [0,1]. Individuals exhibiting frequencies out of this range are considered degenerate and are penalized, i.e. they are assigned a performance value of 1. This same penalization principle could also be used for those individuals having a total length greater than 25.4 mm. It is, however, obvious that the criteria on the length (as small as possible) and frequency (as low as possible) are contradictory. Therefore, it can be expected that a natural equilibrium is eventually reached between these parameters.

IF L < 25.4 THEN B1 = exp(0.721 · L – 18.326)
ELSE B1 = 1

L is the total length of the motor, in mm. For L = 20mm, B1 = 0.02, and for L = 25.4mm, B1 = 0.98. Additionally, if L > 25.4mm, then B1 = 1.

IF F1 > 20 THEN B21 = exp(0.097 · F1 – 5.858)
ELSE B21 = 1
IF F2 > 20 THEN B22 = exp(0.097 · F2 – 5.858)
ELSE B22 = 1

F1 and F2 are the resonance frequencies of the two stator modes, in kHz. For F = 20kHz, B2 = 0.02, and for F = 60kHz, B2 = 0.98. Additionally, if F < 20kHz, then B2 = 1.

B31 = exp(-19.459 · K1 + 1.926)
B32 = exp(-19.459 · K2 + 1.926)

K1 and K2 are the effective electromechanical coupling coefficients of the two stator modes. For K = 0.3, B3 = 0.02, and for K = 0.1, B3 = 0.98.

B41 = exp(-2.595 · U1 + 1.277)
B42 = exp(-2.595 · U2 + 1.277)

U1 and U2 are the vibration amplitudes for each resonance mode, in µm. For U = 2 µm, B4 = 0.02 and for U = 0.5 µm, B4 = 0.98.

B5 = exp(-19.459 · E +13.601)

E is the eccentricity of the vibration ellipse. For E = 0.9, B5 = 0.02, and for E = 0.7, B5 = 0.98.

Objective = [2 · B1 + 4 · (B21 + B22) + 8 · (B41 + B42) + B5] / 27

Figure 13. *Description of the objective function used in the problem. In most cases, it is convenient to determine an exponential fit such that a "good" parameter value is evaluated as 0.02, and a "bad" value as 0.98. In addition, the evaluation result may be imposed to 1 if undesirable parameter values are found. A weighed average of all the parameters is then performed. As a result, the objective of a "good" individual will be close to 0, while that of a "bad" individual will be close to 1.*

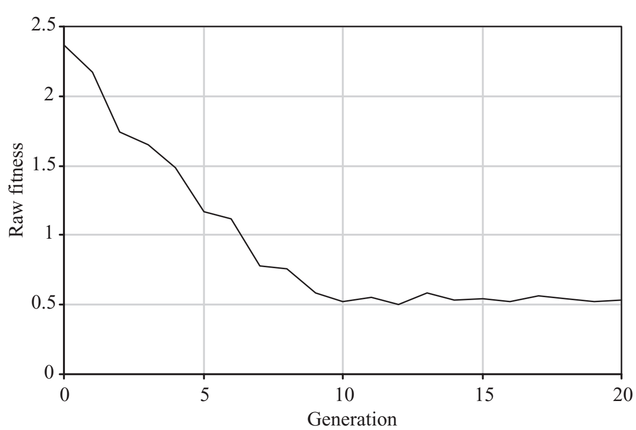


Figure 14. *Progress of the FEA + GA method toward an optimum individual. This illustrates the rapid convergence quality that is typical in genetic algorithms.*

The progression of the average performance value of the population is shown in Figure 14. This figure also clearly illustrates why the genetic algorithm is reputed for converging rapidly toward an optimum of the domain space, but for experiencing difficulties in "fine-tuning" the values of the parameters. The solution generated by the combined FEA+GA method is summarized in Table 2. Values of the computed resonance and antiresonance frequencies of the flexure and tangential modes are given in Table 3.

Table 2. Solution obtained for the optimization problem of the design variables.

Parameter	Dimension (mm)
P1	2.49
P2	12.52
P3	7.39
P4	10.44
P5	10.70

The values obtained for the six design parameters are directly transferred to the mechanical definition of the stator and sent to fabrication. The stator parts are fabricated using the electro-discharge machining technique (Figure 15), except for the metal supports, which are made from gauged steel plates 0.5 mm thick. It was decided to assemble the multilayer actuators at the lab (Figure 16). Each actuator is composed of six piezoelectric plates having a thickness of 1 mm (the material used is the APC841 from American Piezo Ceramics, Inc.). To provide electrical connections, 25µm-thick brass shims were placed in between consecutive plates and at both ends of the stack. Thus, a total of seven brass shims were used in each one of the piezoelectric stacks. The piezoelectric elements and brass

Table 3. Computed modal response for the final individual.

	Resonance Frequency (kHz)	Antiresonance Frequency (kHz)	Electromechanical Coupling Coefficient (%)
Flexure mode	42,551.7	43,951.8	25.04
Translation mode	42,556.3	43,922.8	24.75

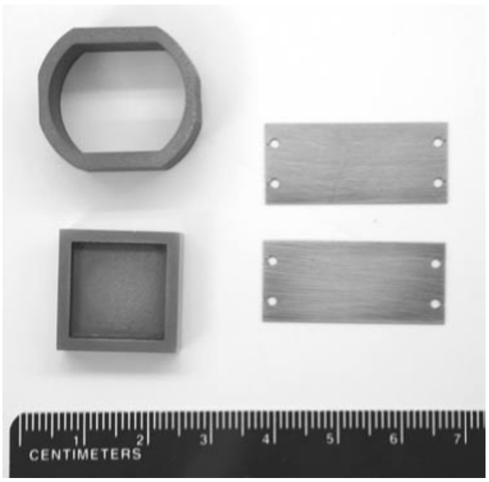


Figure 15. *Metal parts for the stator prototype machined according to the dimensions determined by the optimization procedure.*

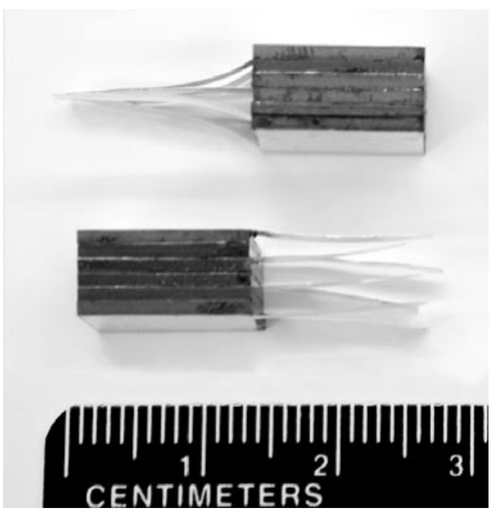


Figure 16. *Piezoelectric stacks assembled at the lab. They are made of six layers of hard-type piezoelectric ceramic. Brass shims are placed in between the piezoelectric layers to provide electrical contact.*

shims were then bonded together using the Stycast 45LV epoxy from Emerson & Cuming. The epoxy was then cured at moderate temperature (50°C) so as not to damage the piezoelectric ceramics. A constant pressure was applied to the stacks throughout the whole curing process by means of a spring-loaded device.

The stator was then assembled (Figure 17) and the various parts (center mass, ceramic stacks, supports, and shell) were mounted and aligned. Finally, the stator was attached to a rigid support by means of #1 screws, and electrical wires were connected.

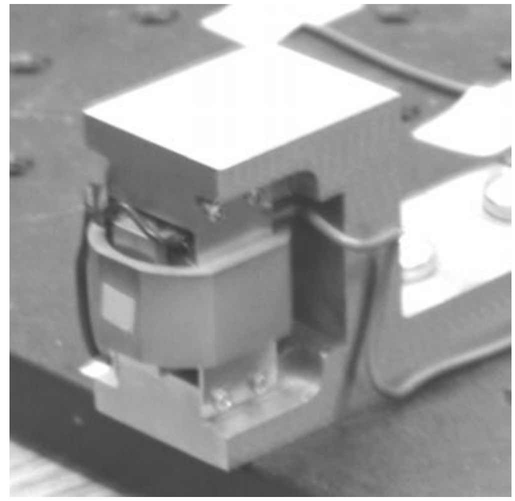


Figure 17. *Assembled prototype.*

Vibration tests performed with a laser interferometer revealed the presence of the desired modes in the neighborhood of 40 kHz (Figure 18). The tangential mode was obtained at 43.0 kHz and the flexure mode at 37.3 kHz. These results can be considered satisfactory (less than 2% error on the tangential mode and 12.5% on the flexure mode) given that this is the first iteration of the design, fabrication, and assembly of this prototype, and that the finite element models were significantly simplified and based on manufacturer data (not experimental) for the materials. The models therefore contain inherent errors that could be reduced by iterating on this process.

Although spurious modes, visible in the measurements, perturb the response of the device, it was possible, by selecting a frequency between 37.3 and 43.0 kHz, to measure the elliptical trajectory of a point on the contact interface. Figure 19 shows some of these ellipses obtained at 39 kHz and for a varying phase angle between the signals exciting the two ceramic stacks. These results demonstrate that the design is, in this respect, successful and that good control of the vibration ellipse can be achieved. When both stacks are excited in phase, for instance, the ellipse is nearly reduced to its normal component. By increasing the phase between the signals, a rounder ellipse forms, until it becomes almost reduced to its tangential component when both signals are in opposition of phase. In this last case, there remains a normal component to the vibration (the ellipse is not quite horizontal), most likely due to spurious flexure at the contact interface.

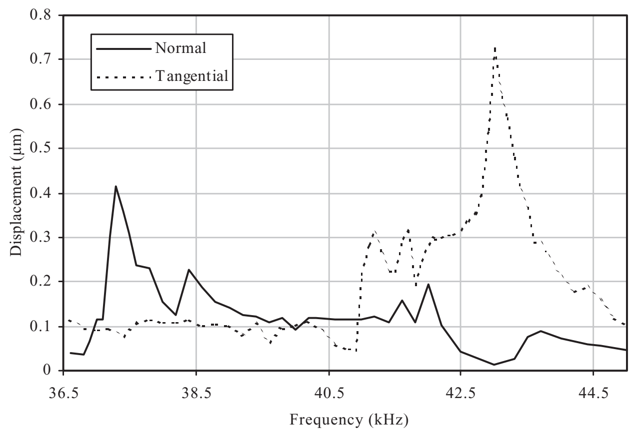


Figure 18. Vibration measurement at the tip of the stator shell. The two desired modes are visible.

The design of the stator was successful in that it allowed defining a structure with the desired modes of vibration, and that these modes operated as expected, i.e., they made it possible to control the shape of the vibration ellipse. Unfortunately, initial design choices for the piezoelectric stacks and mechanical supports proved inadequate, and the prototype performance remained somewhat limited. In particular, the shape and construction of the piezoelectric elements did not allow for the predicted vibration amplitude to be actually generated, and tests for the loaded stator could not be carried out. It is clear that such technological problems could be easily solved, and that an iteration of the prototype would bring the performance to a much more acceptable level. However, this was not considered necessary within the scope of this work because this structure is commercially available and its performance has already been thoroughly evaluated.

CONCLUSION

In this paper, an original method that helps in designing ultrasonic motors was presented. Although based on known methods, namely FEA and genetic

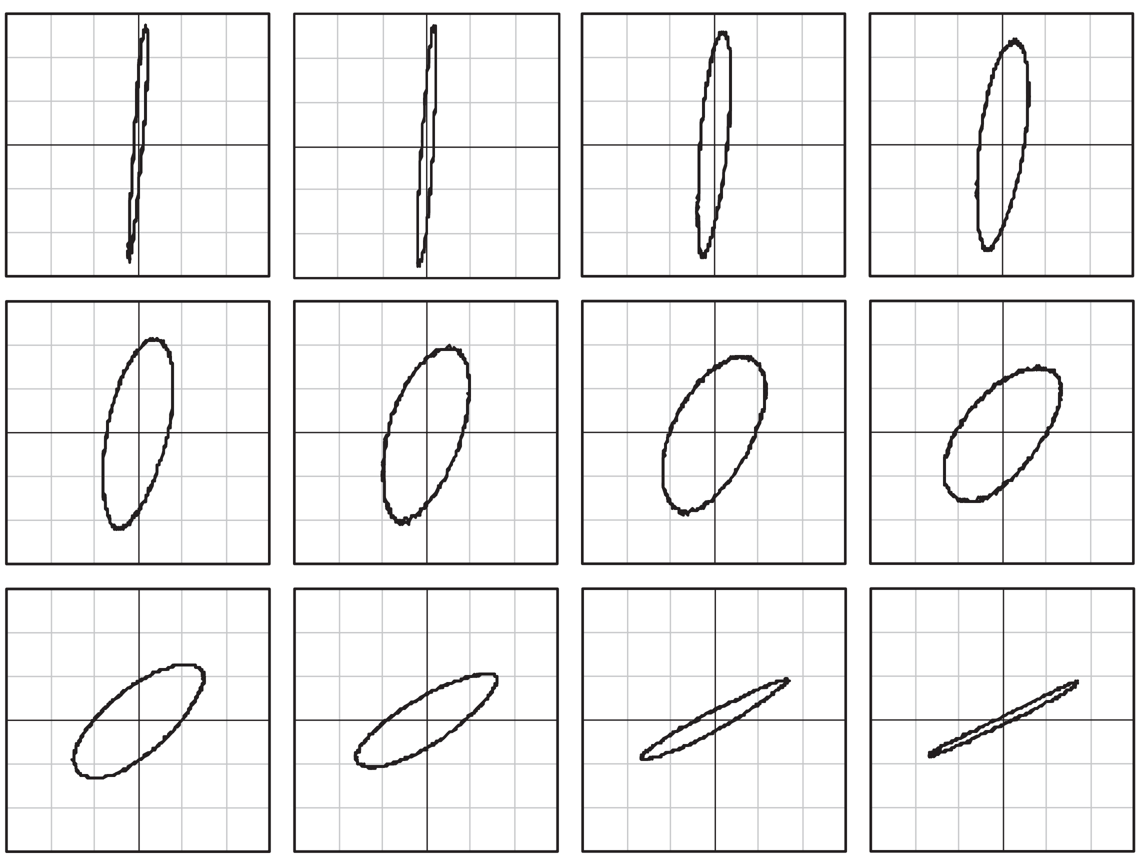


Figure 19. Elliptical vibration trajectories recorded at the contact interface for varying phase angle between the excitation signals. In the top-left image, the phase angle is 0°. There is an increment of 15° between two successive images. In the bottom-right image, the phase angle is 165°.

optimization, this method is innovative and offers a new approach to the complex problem of ultrasonic motor design.

The validation example, based on the design of a commercial motor structure, was successful in that it provided a prototype exhibiting the behavior that was anticipated (modal frequencies at about 40 kHz and control of the vibration field demonstrated). However, poor initial design choices and technological difficulties that were not included in the models have limited its performance. In particular, one of the two structural modes was off by more than 10% in frequency and cause the combination of the modes to be difficult.

It must be noted, however, that the prototype presented here was the first and only one fabricated. No iterations or corrections were made in the design, fabrication, and assembly of the device. This is an important point because it shows that the proposed method yields well-behaving systems. It can therefore be used to test and validate conceptual designs with reasonable faith.

Finally, a natural extension of the method would be to implement the analysis of the contact mechanism within the evaluation of an individual. To achieve this, methods based on modal decomposition and equivalent circuit representations of the contact mechanism could be added to the general program. After evaluating the performance of an individual, the electromechanical characteristics of the system (computed by ATILA) would be used to determine the values of the equivalent circuit (which may be problem dependent). An analysis of the contact problem would reveal the transmitted force and velocity to the rotor or linear guide. Therefore, the evaluation of an individual could be performed directly on the performance it yields at the rotor level. With this addition, the method would enable modeling and optimization of complete motors in loaded conditions.

REFERENCES

Andre, J., Siarry, P. and Dognon, T. 2001. "An Improvement of the Standard Genetic Algorithm Fighting Premature Convergence in Continuous Optimization," *Advances in Engineering Software*, 32(1):49–60.

ATILA: Finite Element Analysis Program for Piezoelectric Structures, Distributed by Magsoft Corp., Troy, NY.

Bouchilloux, P., Le Letty, R., Lhermet, N. and Claeyssen, F. 1997. "Computer Aided Modeling of Induced Strain Actuators and Other Piezoelectric Structures," In: *Proceedings of the ASME: Dynamic Systems & Control Division*, DSC-Vol. 61, pp. 307–312.

Claeyssen, F., Le Letty, R. and Lhermet, N. 1998. "Piezoactive Motor Based on Independent Stator Modules," United States Patent No. 6147436.

Holland, J.H. 1975. *Adaptation in Natural and Artificial Systems*, University of Michigan Press, Ann Arbor.

Koc, B., Bouchilloux, P. and Uchino, K. 2000. "Piezoelectric Micromotor Using a Metal-Ceramic Composite Structure," *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, 47(4):836–843.

Lih, S.-S., Bar-Cohen, Y. and Grandia, W. 1997. "Rotary Ultrasonic Motors Actuated by Traveling Flexural Waves," *SPIE Transactions on Smart Structures and Materials*, 3041:697–701.

Lee, E.T. and Lee, M.E. 1999. "Algorithms for Generating Generalized Gray Codes," *Kybernetes*, 28(6–7):837–844.

Le Letty, R., Claeyssen, F., Barillot, F., Six, M.F. and Bouchilloux, P. 1998. "New Linear Piezomotors for High Force/Precise Positioning Applications," 1998 IEEE Industry Applications Conference, Thirty-Third IAS Annual Meeting, Vol. 1, pp. 213–217.

Le Letty, R., Claessyen, F., Gonnard, P. and Lhermet, N. 1995. "Design of a Mode Conversion Ultrasonic Motor Using an Electromechanical Circuit Analysis," *1st World Congress on Ultrasonic*s.

Le Letty, R., Claeyssen, F., Lhermet, N., Hamonic, B., Decarpigny, J.N. and Bossut, R. 1997. "Combined Finite Element – Normal Mode Expansion Methods in Electroelasticity and their Application to Piezoactive Motors," *International Journal for Numerical Methods in Engineerin*g, 40:3385–3403.

Uchino, K. 1997. *Piezoelectric Actuators and Ultrasonic Motors*, Kluwer Academic Publisher, ISBN 0-7923-9811-4.

Ueha, S. and Tomikawa, Y. 1993. *Ultrasonic Motors – Theory and Applications*, Oxford University Press, ISBN 0-19-859376-7.Zhang, B. and Zhu, Z. 1997. "Developing a Linear Piezomotor with Nanometer Resolution and High Stiffness," *IEEE/ASME Transactions on Mechatronics*, 2:22–29.

Zhang, B. and Zhu, Z. 1997. "Developing a Linear Piezomotor with Nanometer Resolution and High Stiffness," *IEEE/ASME Transactions on Mechatronics*, 2:22–29.