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THE DESIGN OF A SATELLITE BOOM WITH ENHANCED VIBRATION PERFORMANCE USING GENETIC ALGORITHM TECHNIQUES

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ABSTRACT

This paper examines the application of passive vibration control methods to a simplified satellite boom. It is suggested that such methods may allow an efficient means by which to control structural vibrations. In this research, an initial structure is designed having a regular, repeating geometric pattern. This design is then modified using a Genetic Algorithm (GA), which is one of a number of recently developed evolutionary computing methods. Here the GA changes the geometry of the design by altering the three-dimensional coordinates of its joints. The aim is to minimize the band averaged noise transmission along the boom. This paper shows that by altering the geometry in this way, significant improvements in the structure's noise performance can be achieved. While this research is far from complete, the work outlined demonstrates the potential usefulness of this approach for controlling structural vibrations.

INTRODUCTION

In the design of practically all engineering structures and machines it is desirable to minimize mechanical noise and vibrations. Vibrations can have catastrophic effects on the performance of a structure. When considering solutions to vibration and noise problems in engineering structures, at least three possible strategies may be considered. The first, and presently most popular, option is to incorporate some form of vibration absorbing material into the design of the structure. For example, one might elect to coat the structural elements with a heavy viscoelastic damping material. Similarly, pieces of vibration isolating material could be placed at mounting points, as is the case with most automobile engines. However, this method has rather significant weight and cost penalties. In the design of aerospace structures this is a major concern, since any increase in weight results in subsequent increases in the cost of deploying the structure or reductions in payload.

The second method is so-called 'active' vibration control. This method employs the use of 'anti-noise' to cancel out unwanted vibrations and hence block noise propagation. However, active vibration control methods are inevitably complex and expensive.

A third option is passive vibration control. In this method, the design of the structure is modified so that it has intrinsic noise filtration characteristics. For example, the work described here shows that the frequency response of a specific structure can be considerably improved by making changes to the structure's geometry. The geometric regularity or irregularity of a structure affects its vibrational response. In the case of a satellite boom, a geometrically regular structure would be one in which the lengths of beam elements and the angles between them were repeated numerous times along the length of the structure. An irregular geometry would be one in which no two beam lengths or angles were equal.

By considering a very large number of different geometries, a design with superior noise performance can be achieved. In this work, Genetic Algorithm (GA) optimization methods are combined with an energy flow analysis to produce new structural geometries with improved noise performance.

Energy approaches can be used to predict the flow of vibrations around structures. They are seen by many as the best long term means for analyzing the noise performance of aerospace structures. Here, the vibration analysis is carried out using matrix receptance methods based on the Green functions of the individual beam elements. By combining these receptance methods with the well-known characteristics of Euler-Bernoulli beams, it is possible to solve directly for the energetic quantities of interest(1).

In this work a Genetic Algorithm is used to select the design geometries with the best noise performance. The GA used here is fairly typical of those discussed by Goldberg(2). The method works by maintaining a pool, or population, of competing designs which are combined to find improved solutions. The processes that are used to seek these new designs are set up to mimic natural selection. The most common genetic operations cited in the literature are currently: (a) selection according to fitness, i.e., the most promising designs are given a bigger share of the next generation; (b) crossover, where portions of two good designs, chosen at random, are used to form a new design; (c) inversion, whereby the genetic encoding of a design is modified so that subsequent crossover operations affect different aspects of the design and (d) mutation, where small but random changes are arbitrarily introduced into a design. Before performing an optimization using this method a number of parameters must be chosen, of which the most important are the number of generations and their sizes(3).

GEOMETRIC OPTIMIZATION OF A TWO-DIMENSIONAL STRUCTURE

The work detailed in this paper concerns optimization of the frequency response of a three-dimensional satellite boom. This follows the satisfactory application of GA optimization to a two-dimensional design. In this previous work, the two-dimensional boom consisted of 40 individual Euler-Bernoulli beams connected at 20 joints. Each of the 40 beams had the same properties per unit length. Initially the boom was designed and analyzed for a regular geometry where each beam was either 1.0 m or 1.414 m in length, see Figure 1. The joints at points (0,0) and (0,1) were fixed, i.e., they were fully restrained in all degrees of freedom. The structure was excited by a point transverse force applied halfway between points (0,0) and (1,0). The vibrational energy level was found for the right-hand end vertical beam using receptance methods(4).

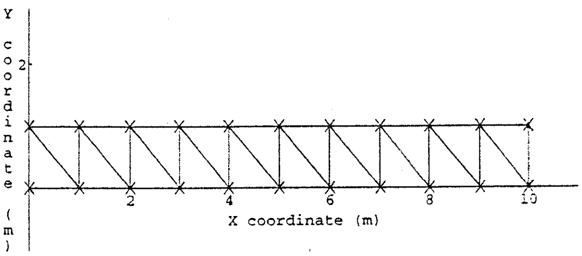

Figure 1 - a simplified, two-dimensional satellite boom.

This regular geometric design was then manipulated by the optimization software(5). The goal of the optimization was set as minimizing the frequency averaged response of the end beam in the range 150-250 Hz. The optimizer was allowed to generate new geometries by varying the coordinates of the inner 18 joints of the structure. To prevent any overlapping of beams and to prevent any beam from becoming too extreme in length, the joints were kept within fixed distances of their original positions; neither the coordinates of the two fixed joints nor those of the right-hand vertical beam being allowed to move.

Upon applying the GA using various values for the population size, number of generations, and limits on the joint positions, the most improved frequency response curve was obtained using 15 generations with a population size of 300 and a ±25% constraint on the joint positions(4). The resulting geometry and frequency responses of the original and improved structures are shown in Figures 2 and 3, respectively.

As can be seen from Figure 3, the frequency averaged energy level between 150 and 250 Hz in the beam of interest has been significantly reduced when compared to that of the boom with regular geometry. The process appears to have produced very favourable results.

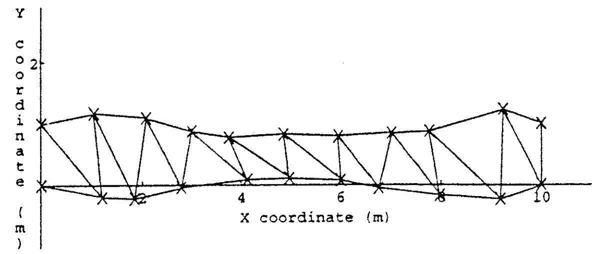

Figure 2 - optimized two-dimensional design with limits of ±25% on all joints, 4,500 evaluations over 15 generations.

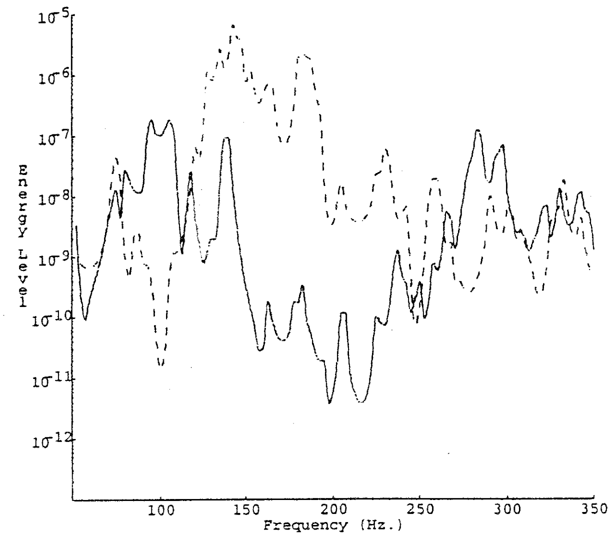

Figure 3 - frequency response of optimized two-dimensional design with limits of ±25% on all joints, 4,500 evaluations over 15 generations, with response for initial design shown dotted.

To test the validity and value of these results, physical models of both the original and final boom designs have been built and tested(6). In order for the models to be of a reasonable size, the beam lengths had to be scaled down. In doing this, it was ensured that the beams used in the physical model had the same fundamental free-free natural frequencies as those used in the theoretical analysis. The physical models were mounted and the forces applied in the same manner as in the theoretical analysis. The energy levels in the beams of interest were measured using appropriate transducers. The resulting frequency responses (as characterized by velocity squared) from testing the physical models are shown in Figure 4. Upon comparison with Figure 3, it is apparent that the results of the theoretical analysis correlate quite well with those from the experimental measurements.

Because of the satisfactory agreement between the results of the theoretical and physical tests, the approach used in this previous work appears to represent a promising method for enhancing the noise performance of a structure using passive techniques. To further confirm this belief and to demonstrate the usefulness of the technique, the same procedure has now been applied to a three-dimensional problem.

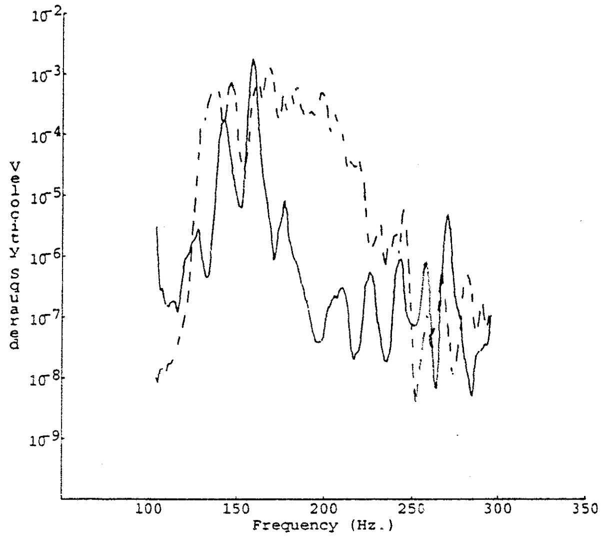

Figure 4 - physical frequency response of optimized two-dimensional design with limits of ±25% on all joints, with response for initial design shown dotted.

GEOMETRIC OPTIMIZATION OF A THREE-DIMENSIONAL STRUCTURE

Introduction

In applying this analysis procedure to a three-dimensional boom structure, the following steps were taken: first, the initial boom design (i.e., a geometrically regular design) was modeled using a commercial computer-aided design package(7). Next, the natural frequencies of the structure were calculated using finite element analysis. A force analogous to that applied to the two-dimensional structure was then applied to the three dimensional boom, and a frequency response curve obtained. A second frequency response curve was then calculated using receptance methods(1). Upon confirmation that the frequency response curves produced by the two methods were similar, the receptance method code was interfaced with the optimization software to carry out the search for new geometries with superior noise performance.

The Structure

The initial structure to be optimized (Figure 5, which also shows the forcing and response points used) consisted of 90 Euler-Bernoulli beams all having the same properties per unit length. Because it is intended that physical models be built of this three-dimensional structure, the overall length of the structure had to be kept within reasonable limits. To ensure that the beams used in the structure had similar frequency responses to those used in the two-dimensional case, the equation for the fundamental free-free natural frequency of a beam was manipulated to form the following relation governing the dimensions of the beams of the three-dimensional structure: $D=0.05393L^2$, where D is the diameter of the beam elements in metres and L is the length of the shorter of the two types of beams used in the structure, again in metres. The physical properties of the beams were based on typical values for aluminium. A diameter was then chosen that would produce a structure of reasonable overall length and that was readily commercially available. 0.25 inch diameter aluminium rods were selected and this results in a beam length of 0.3428 m (i.e., an overall structure length of 3.428 m), EA of 2.25 MN, EI of 5.67 Nm^2, and a mass per unit length of 0.087 kg/m.

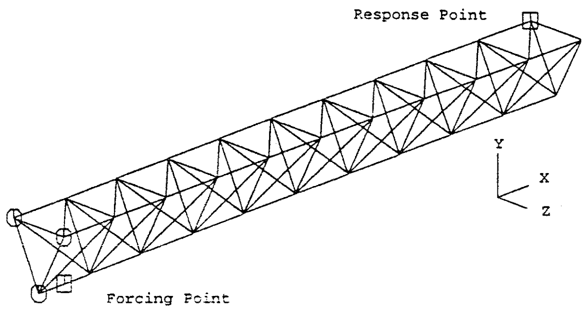

Figure 5 - geometry of initial, regular three-dimensional design, also showing forcing and response points.

The 90 beams were arranged in a similar manner to that of the two-dimensional structure. Essentially, the two-dimensional structure was repeated three times so that the YZ cross-section of the three-dimensional structure formed an equilateral triangle with its apex pointing in the negative Y direction. The three joints at the left-hand end of the structure (i.e., points (0,0,0), (0,0,0.3428), and (0,-0.29687,0.1714)) were clamped so as to prevent motion in any degree of freedom. The 90 beams were then connected by 30 joints, not including the three fixed joints. The direction of the diagonal beams was chosen so that a maximum of six beams met at any one joint. The structure was excited by a point transverse force halfway along the length of the bottom left-most beam (i.e., halfway between the points (0,-0.29687,0.1714) and (0.3428,-0.29687,0.1714)). The damping ratio of all beams in the structure was set at 0.005.

Finite Elements Analysis

Once the three-dimensional boom had been designed, the first step in the optimization process was to produce a frequency response curve of the initial boom design using the commercial FEA package. The output obtained from the receptance method could then be compared against these finite element results to confirm that accurate results were being obtained. Throughout this research, the frequency response curves produced by FEA were used to support and confirm those obtained from the receptance code.

Before defining and generating the finite element mesh, the boom was modeled as a wire frame. In other words, each of the 90 beams in the structure was drawn as a simple line in three-dimensional space. When defining the mesh, the geometric cross-sections of the beams were input along with their properties per unit length. The elements of the mesh were defined as having one-tenth the length of the non-diagonal beams in the structure. Before continuing, this choice of finite element length was validated by showing that, for a single beam, the distance between nodes of the mode shapes for all relevant modes was significantly greater than this element length. Although the frequency range of interest is 150-250 Hz, reliable frequency response curves covering the range 0-500 Hz were studied to ensure confidence in the results. For a single 0.48m beam (the longest in the structure), the seventh mode has a frequency of 659 Hz. As can be seen in Figure 6, the length of one finite element is significantly less than the distance between the nodes of the mode shape, justifying the mesh adopted.

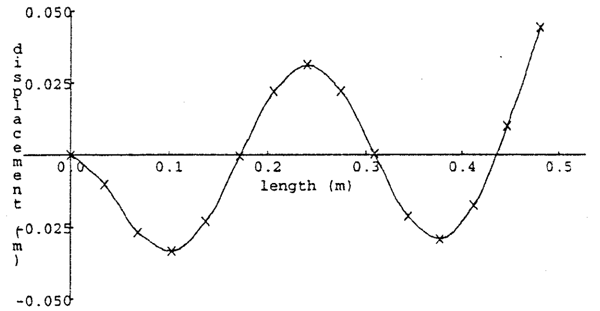

Figure 6 - mode shape of a single beam element calculated using FEA, with crosses marking the individual element ends.

As a final test of the mesh density of the finite element model, the element length was halved, and the analysis for a single beam performed a second time. Whereas modes 6 and 7 had frequencies of 336 Hz and 659 Hz with an element length of 0.03428 m, they have frequencies of 336 Hz and 658 Hz using an element length of 0.01714 m. From these results, it is apparent that the mesh density used during the finite element analysis produces results with accuracy sufficient for the present study. It is, of course, desirable to keep mesh densities low to reduce loads on computer c.p.u. time and memory.

The boundary conditions and excitation force were applied as described earlier, i.e., the three joints at the left-hand end were restrained in all degrees of freedom, and excitation applied as a point transverse force in the positive Y direction at a point halfway along the bottom left-hand beam. The frequency response (i.e., displacement versus frequency) was calculated at the right-hand end of the boom at joint 28, having coordinates (3.428,0,0.3428).

The finite element computation was initially solved for the first 100 modes of the structure, in this case up to a natural frequency of 184 Hz. Subsequently, the model was solved to mode 500 (1,090 Hz) and to mode 800 (2,170 Hz). Solving for 800 modes takes approximately 12 hours of c.p.u. time here using a Silicon Graphics R4400 based machine. In the range of interest (150-250 Hz), no noticeable discrepancy can be seen between the frequency response curves obtained during the 500 mode solution and the 800 mode solution. Thus, confidence can be expressed in the results obtained for this range. Figure 7 shows the displacement in the global Y direction of joint 28 as a function of driving frequency in the range 150-250 Hz (along with that from the receptance theory).

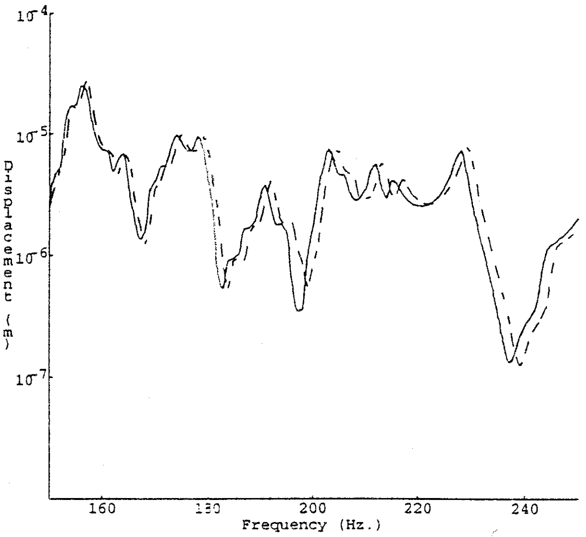

Figure 7 - frequency response of initial three-dimensional design calculated using FEA, with response found using receptance theory shown dotted.

Receptance Theory

The next step in this study was to produce a frequency response curve similar to the solid line in Figure 7 but using receptance theory. The program used reads a formatted description of the three-dimensional boom from a data file. The information contained within this file is identical to that input during generation of the finite element model. Essentially, the data file consists of (a) a listing of all beams meeting at each of the 30 joints and (b) a listing of all properties for each of the 90 beams.

Upon running the analysis, the program first reads in the information from the data file and then prompts the user to specify (a) the frequency range over which to solve; (b) the number of data points to calculate within the specified frequency range; (c) the element or joint numbers at which to calculate the energies or displacements and (d) the number of axial/torsional and transverse modes used in the modal summations for the

Green functions. The behaviour of the global structure is predicted from the Green functions of the individual uncoupled beams, evaluated as summations over their mode shapes. Shankar and Keane(1) provide a comprehensive discussion on the theory, creation, and testing of this code.

To produce a frequency response that can be compared with that produced by the finite element analysis, the program was run for a frequency range of 150-250 Hz using 101 data points. The output was set as the displacement of joint 28 and the number of modes used to describe each individual beam set at 200, which guarantees convergence of the Green functions. This calculation took about four and a half hours to complete. The resulting frequency response curve is also shown in Figure 7. On comparison with the results of the finite element analysis, the two curves are virtually identical (the slight frequency shift of around 1% being due to the inherent limitations of FEA with finite mesh sizes and solution accuracy). Therefore, confidence may be expressed in the output of the receptance code.

It should also be noted that the time taken to carry out the FEA analysis is dominated by the number of elements used while the receptance method is influenced strongly by the number of frequency points to be studied (it is, of course, also affected by model size). Thus, although the FEA takes around twice as long to carry out as the receptance code when examining 101 frequencies, it takes roughly ten times as long when dealing with the reduced set of frequencies needed for optimization (here a 21 point integration rule is applied to assess band averaged frequency response). The receptance method's principal attraction over FEA is therefore the speed with which an individual design can be analysed for its band-averaged performance. Moreover, the receptance code used can be interfaced more easily to the optimization software used here and can readily be run in parallel on multiple processors when carrying out design searches.

Optimization

Given that the reliability of the receptance code had been proven, it was then interfaced with the optimization software(5). The goal here was to produce a new boom geometry with an improved frequency response curve. More specifically, the aim was to reduce the frequency averaged magnitude of the normalized energy flow into the end-most horizontal beam over the frequency range 150-250 Hz.

Having specified this goal, a GA optimizer was selected from the optimization package to produce superior designs. For this particular run of the GA, the number of generations was set as 10 and the population size as 100. During the first generation, the optimizer generates 100 random new geometries. In the creation of a new geometry, the coordinates of all joints in the structure (with the exception of those at the extreme left and right-hand ends of the boom) were varied within some specified maximum deviation from their original positions, here ±25%. After analyzing the frequency response of each of these new boom designs, the GA outputs the design with the best performance and then continues on to the second generation. The designs carried over to the second generation and the creation of subsequent new designs are governed by the specific 'natural selection' algorithms employed by the GA. The completion of the first ten generations took approximately 2,000 c.p.u. hours which, using parallel processing, took around 20 days. This extremely large c.p.u. effort explains why so few generations were used and why only 100 members were allowed for each one. Clearly, with 3×27=81 variables, a rather larger generation size would have been desirable, as would more generations. Nonetheless, as will be seen, significant performance improvements were obtained.

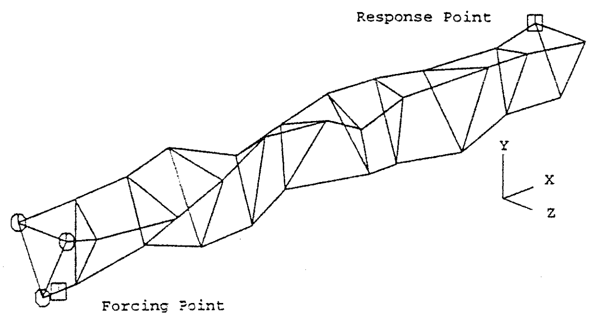

Figure 8 - geometry of best three-dimensional design found in first, random generation (diagonal elements omitted for clarity).

The geometry producing the best frequency response curve from the 100 random geometries created during the first generation is displayed in Figure 8. As can be seen, the locations of all of the 'interior' joints have been significantly changed. To provide a clearer picture of the overall geometry of the new design, the 'diagonals' have been omitted from this figure; they were, of course, included during the computations.

To confirm that the optimizer had indeed produced a geometry with an improved frequency response curve, the new structure was again modelled and analyzed using the commercial finite element software. The same boundary conditions were applied as before, i.e., the three extreme left-hand joints were restrained in all degrees of freedom. A point transverse force was applied in the positive Y direction at a point 0.1714 m along the length of the bottom left-hand beam (i.e., half the length of the original beam). The response was measured at the same joint as before (which remains at the same coordinates in space). The resulting frequency response curve is shown in Figure 9, along with that produced using the regular geometry (i.e., that of Figure 7). It is obvious from this graph that this initial random search has indeed produced a design with an improved frequency response. The magnitude of the displacement at joint 28 has been decreased across most of the frequency range of 150-250 Hz.

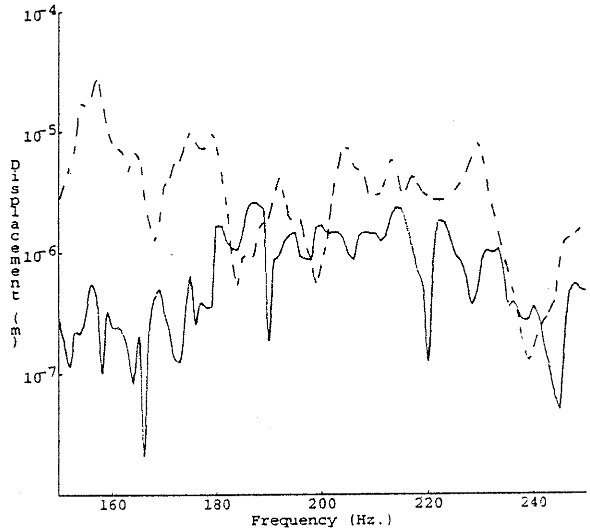

Figure 9 - frequency response of best three-dimensional design found in first, random generation, with response for initial design shown dotted.

The next step in the optimization process was to run the GA for more generations. Figure 10 shows the change in the mean, standard deviation, and minimum value of the objective function of the GA over the ten generations used. As has already been noted, the objective function is the normalized average energy in the end horizontal beam taken over the specified frequency range. Therefore, at any given stage, the boom design with the best frequency response curve is represented by the 'minimum' curve in Figure 10. The initial value of the objective function (i.e., before generation 1) was 0.0365. At the conclusion of the first generation, the value of the objective function for the best design was 0.000650, an improvement of over 5,000%. This was followed by less dramatic, but nonetheless substantial improvements, with the final objective function being 0.000173, a reduction of a further 380%. Figure 10 also shows that the generational mean steadily decreased across all generations and that the generational normalised standard deviation showed a generally downward trend. The fact they the deviation was still roughly equal to the mean at the last generation indicates that the populations had by no means become stagnant and that further generations could have been expected to improve the design still further. It is unlikely that any massive additional improvement would be made to the objective function value, but it should be possible to further tune the designs so that the generational mean and minimum start to converge and the standard deviation drops to significantly lower levels.

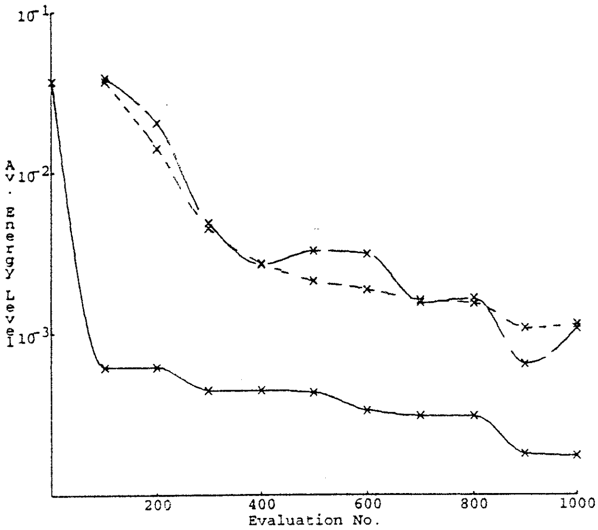

Figure 10 - variation of objective function with evaluation number, with generational mean shown dotted and generational normalised standard deviation dashed.

This behaviour (a huge initial improvement followed by more modest refinements) reflects what one would expect. It is well known that a geometrically regular design does not produce a particularly favourable frequency response curve. Conversely, an irregular geometry has the *potential* to produce significant improvements in the frequency response (many irregular designs are, in fact, worse). This knowledge represents the foundation of the present research. Therefore, it is not surprising that a very large improvement has been achieved by choosing the best out of 100 irregular geometries. During subsequent generations, this irregular geometry is then 'fine tuned'. With the first generation, a good base design is found. Subsequent generations provide steady, but less dramatic, improvements of a similar magnitude throughout the run. This is a direct consequence of the limited number of trials allowed by the time consuming analysis underpinning the work. In such cases it is unrealistic to aim at achieving globally optimal designs, instead good improved designs have to be sufficient. Even so, dramatic performance improvements have been obtained, see figure 11, which shows the frequency response for the final design, along with that for the best in the first, random generation. Figure 12 shows the final geometry achieved, c.f., figures 5 and 8. Although these modified geometries may appear extreme when compared to the original design, they do provide the required noise isolation characteristics. Clearly, they would not be simple to build or deploy, but then neither are 'active' control systems. In fact, a combined approach might well offer the best of both worlds.

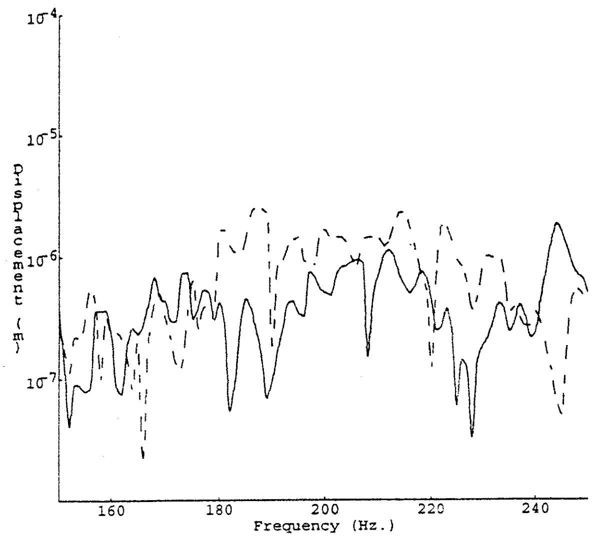

Figure 11 - frequency response of final three-dimensional design, with that for the best design found in the first, random generation shown dotted.

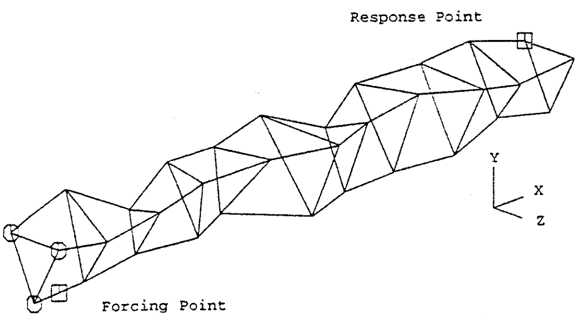

Figure 12 - geometry of the final three-dimensional design (diagonal elements omitted for clarity).

CONCLUSIONS

This paper has shown that significantly improved frequency responses may be obtained for three-dimensional beam structures using Genetic Algorithm optimization procedures. However, in order to accurately assess the designs considered by the GA, very significant computations are required, even when using a highly tuned and customized code to carry out these calculations. This leads to very long run times, necessitating the use of parallel processing, if realistic studies are to be undertaken.

Although only at an early stage, the work presented shows that improvements of over 20,000% in frequency averaged energy levels can be obtained following this approach. Most of this improvement is seen to be due to the selection of promising design types during the first, randomly selected, generation of the GA. However, further calculations over succeeding generations then allow another 380% reduction in the energy transmitted through the structure. The nature of these changes suggests that, despite the massive improvements obtained, the GA is not likely to have found the globally optimum design in this study. This would seem to be an inevitable result of dealing with a problem with 81 variables using only 1,000 function evaluations. As such, it once again demonstrates that, in many cases of engineering interest, global optima cannot be found with current levels of computing power. In such cases, rapid convergence to improved designs must remain the real goal of the designer.

This research is continuing, and a more fully-optimized version of the three-dimensional structure is anticipated in the near future. Once this final design has been obtained, it is the intention of the research group involved to build and test a physical model of the boom design, just as was done in the case of the two-dimensional structure.

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