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Multi-Modal Dynamic Vibration Absorber Design for Aerodynamic Surfaces Using Optimization

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Abstract. Dynamic Vibration Absorbers (DVAs) are devices that aim to reduce the vibration amplitudes of systems subjected to external forces. When a DVA is coupled to a primary system, it promotes the reduction of vibration at a certain frequency of operation. The aerodynamic surfaces of aircraft, such as wings, are subject to problems, for example, those caused by the Flutter effect, dangerous phenomenon found in flexible structures subject to aerodynamic forces such as aircraft, buildings, bridges, among others. This phenomenon is characterized by the coupling of two oscillations, flexion and torsion, which occurs due to the interactions between aerodynamics, low stiffness and inertial forces in a structure. In order to simultaneously mitigate the amplitudes of vibration in the vicinity of both oscillations in the wing, this work proposes the design and optimization of a passive MultiModal DVA (MMDVA) whose main feature is the ability of reducing vibration at the vicinity of various resonance frequencies of a primary structure. This justifies why it is used in the current application. However, it is not easy to determine the optimum constructive parameters of these MMDVAs and therefore it is necessary to use optimization methods to guarantee that they are tuned to the wing frequencies (flexional and torsional). The global optimization heuristic Genetic Algorithms (GAs) was used for this purpose and demonstrated to be efficient.

Keywords: Multimodal Dynamic Vibration Absorber (MMDVA), Wing, Optimization, Genetic Algorithms

1 Introduction

Since the drawn of engineering, it became common to build taller, slender and lighter structures for application in various fields of knowledge. However, these structures are prone to have smaller resonance frequencies with high amplitude, thereby shortening the useful life of them or making their use harmful to humans that operate them. To minimize these effects, vibration absorbers were created in order of reducing and controlling the vibrations of structures and machines. Hermann Frahm [1] was the pioneer and inventor of the first Dynamic Vibration Absorber (DVA) in 1911, from that, several works were published with the objective of exploring different ways to increase the performance in systems subjected to vibrations. Discrete DVAs that use predefined mass, stiffness and damping properties transmit forces against the structure (where it is installed) and dissipate energy. Despite its mechanical simplicity, they are capable of generating efficient damping over a small range of frequencies, only at the vicinity of the fundamental frequency of the primary system where it was tuned [2]. Slight deviation from the parameter setting can result in a significant decrease in the vibration reduction performance when a single DVA is used. In practice, engineering structures possess multiple vibration modes, which renders the tuning procedure more complicated than when considering the single mode assumption [3].

According to [4], in order to tackle the shortcomings associated with single DVAs and get a robust vibration control performance, multiple or distributed dynamic vibration absorbers (MTMD) are usually used for suppressing vibrations. This approach is usually used to reduce the vibrations in continuous structures but, considerable space need to be available along the structure and a detailed study about the number and position of multiple DVAs have to be done. In the present work, a less common type of DVA is explored, it is known as Multi-Modal DVA (MMDVA). A single MMDVA allows to keep the best features of a single passive DVA like low maintenance/cost and no energy consumption but in addition, have the capability of be tuned to more than one frequency such as MTMDs, economizing space. In [5] an approach for simultaneous control of major horizontal, vertical and torsional modes is presented targeting robust vibration control of a bridge using the traditional approach of MTMDs.

In the present work, a innovative MMDVA is designed in order to mitigate the vibration response of a structure, specifically an aerodynamic surface (aircraft wing), using a single device tuned to the dominant flexional and torsional modes of vibration.

The MMDVA have to be properly tuned to each mode of vibration and at the same time must be lighter enough to avoid increasing the total weight of the structure. In [6] was mentioned that in structures like the wing of an aircraft, vibration can be a very critical issue due to have more than one resonance frequency. The MMDVAs features make it attractive for applications in structures with multiple natural frequencies of vibration, especially if they are low (easy to reach), with multiple dominant directions. Even more, if the resonance frequencies are close to each other, as in light and long structures like aircraft wings, highly subject to the Flutter event (self-excited vibrations caused by aero elastic effects).

Finally, it should be noted that MMDVAs are devices with complex geometry and multiple degrees of freedom, so the problem of finding its design parameters does not have a trivial solution. Optimization algorithms are efficient tools that help to determine the optimal design/manufacturing parameters in this type of case. Global optimization heuristics like Genetic Algorithms (GAs) ensure that the solution found is the best for the predefined conditions and as a consequence prevents lower quality solutions (local minimums) from appearing. According to [7] new evolutionary global optimization techniques have been proposed, among them, particle swarm optimization (PSO, Particle Swarm Optimization), Ant Colony Optimization (ACO, Ant Colony Optimization) and Genetic Algorithms (GA , Genetic Algorithms). Each with its particularities, precision and convergence rates. Then, the main objective of the present study is the use of GAs optimization technique in order to obtain the design parameters of a MMDVA capable to mitigate the vibration amplitude of an aircraft wing at several vibration modes, such that flexional and torsional dominant modes.

2 MMDVA Design Methodology

In order to guarantee that the MMDVA will be able to attenuate mechanical vibrations in a higher excitation frequency range, these range or specific frequencies must be pre-established by the designer. As explained previously, the frequencies where the DVA have to work must be the same as the primary structure. The process of ensuring that the same device, modelled with a continuous structure simultaneously show these frequencies is not a simple task, for this, an optimization method is employed and requires at the same time, the definition of a function that measures which values of the design parameters satisfy this condition and, when it need to stop the process (since it is an iterative process). In the present work the process adopted is based on the work of [8]. The methodology applied for this purpose is illustrated in Fig. 1.

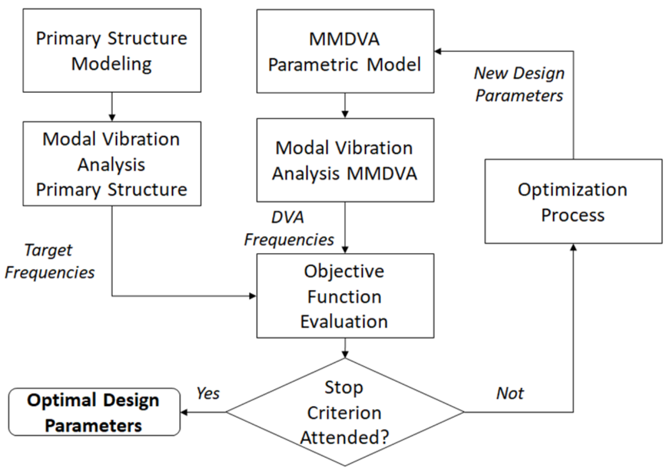

Figure 1. MMDVA Design Methodology

According to Fig. 1, the process begins with the modelling of the primary structure and the extraction of its natural frequencies. The primary structure is a simplified model of an aircraft wing. Due to the purpose of the MMDVA is the attenuation of fundamental flexional and torsional frequencies, they must be identified by performing a modal vibration analysis and observing the physical mode shapes and their respective frequency, which will be the target frequencies, that is, the frequencies that the MMDVA must tune in.

In parallel, the MMDVA (or secondary structure) is modelled with the aid of the Finite Element Method (FEM) and a commercial software. The model is parametrized defining its design variables (material, dimensions, et.), these are also known as design parameters. This process allows to obtain the natural frequencies of the MMDVA for certain design parameters. Then, both, the frequencies of the primary (wing) and secondary (MMDVA) systems are compared. A strategically objective function is chosen to this end will indicate how close they are and allows to decide based on a stopping criterion (number of iteration, value of the objective function itself, etc.) if the parameters are optimal or not. Once the criterion is attended can be guaranteed that the MMDVA frequencies matched the target frequencies of the wing. If this is not the case, an optimization process is carried out.

The optimization process ”analyses” at each iteration several sets of design parameters and makes modifications to them. Then, based on their quality in the evaluation of the objective function, are created more and more efficient sets of parameters according to the desired objective. Global optimization heuristics, in this case Genetic Algorithms (GAs) have been shown to be efficient in this task, as demonstrated in [8]. In GAs optimization method, iterations are called generations and each set of parameters is called ”individual”, at each generation, a fixed number of different individuals are created, crossed and randomly modified (mutated) in such a way that a new set of individuals are created. Finally, these new individuals are inserted back into the parametrized model of the MMDVA to close the loop of the iterative process.

3 Numerical Primary Structure Modelling and Analysis

3.1 Wing Modelling

The Finite Element Method (FEM) is a valuable tool for modelling and simulating engineering systems. The FEM analysis from a practical point of view ensures greater efficiency and cost-benefit in structural design, especially because it reduces the amount of experimental tests to be performed and allows the optimization of its characteristics prior to the construction, as in the present work. FEM basic working principle is based on the assumption that a structure can be divided into elements of finite dimensions, called ”finite elements”. This phase of the method is also known as ”discretization” when related to continuous structures modelling. The fundamental concept of FEM is that any continuous amount of a structure such as displacements, stresses and strains can be approximated by a discrete model composed of a set of continuous functions defined over a finite number of subdomains. These series of functions are continuous in parts and must address the exact solution as the number of sub-domains approaches to infinity [9].

In this work, the geometric modelling of the primary structure is performed in commercial CAD (Computer-Aided Design) software and then imported into CAE (Computer-Aided Engineering) software. As commented in previous sections, the primary structure is an aircraft wing. A simplified model of an aircraft wing was designed in this work for the present application. It is a rectangular wing of constant transversal section of one meter chord and two meters wingspan. NACA0010 airfoils (symmetrical) were used for the ribs, and attached to rectangular section stringers (forward and after). Thin metal plates are used to represent part of the wing' skin on the leading and trailing edges (see Figure 2). Assuming that the stringers are perfectly attached to the fuselage , the boundary conditions were adopted considering the stringers as cantilever beams.

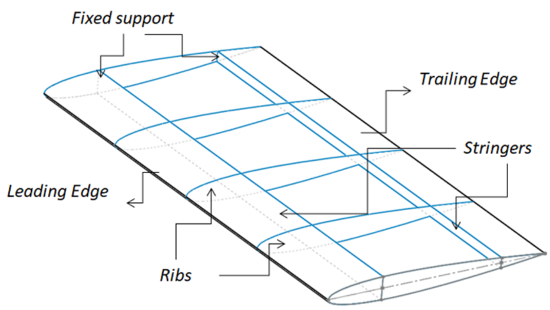

Figure 2. Wing Structural Elements

The wing structure was modeled using FEM. All parts were modeled using a shell type quadrilateral element with six Degrees of Freedom (DOF) at each of its four nodes (SHELL181), that is, translations and rotations along the three main reference axes (x, y and z). The isotropic material adopted for the modelling was aluminium whose main properties are: Young Modulus $E = 70GPa$, Poisson ratio $\epsilon = 0.33$ and density $\rho = 2710kg/m^3$. Due to the fact that the CAD model was developed considering only surfaces, at the CAE software it was possible to add thickness to shell elements, the thickness was chosen as $t = 5mm$ for the plates that compound the leading and trailing edge, ribs and stringers. The mass of the wing structure is 33.604 kg, this value is important to define the maximum allowable mass of the MMDVA. In adddition contact elements were defined in order to joint all the surfaces. To make the mesh, 20 divisions were used in the direction of the chord to capture better the shape of the airfoil, 10 divisions along the wingspan, and 4 divisions in the vertical direction (y-axis). Fig. 3 shows the numerical model of wing and its boundary conditions.

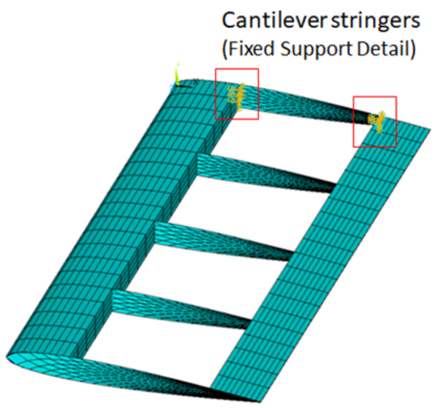

Figure 3. Wing Mesh and Boundary Conditions

3.2 Primary Structure Vibration Analysis

The modal analysis was configured so that the first ten vibration modes were extracted within the frequency range of 0 to 200 Hz, this frequency range was considered due to the very low stiffness expected of the structure due the use of thin plates. As previously mentioned, boundary conditions were applied to the structure in order to better represent the connection of the wing with the fuselage. This was done by restricting the displacement of the nodes that compose the rectangular section of one of the ends of the ”Beams” that represent the stringers. The modal analysis was performed assuming free vibration, that is, without considering the presence of an unbalance engine installed in the wing, that is, without external forces. Table 1 resume the first three modal vibration modes and its corresponding frequencies and Figure 4 illustrates the physical displacement of the structure at each mode (modal shapes).

Table 1. Primary structure vibrations modes and frequencies

Mode	Type	Frequency (Hz)
1	Flexional (around ”y” axis)	$\omega_1 = 3.7122$
2	Flexional (around ”x” axis)	$\omega_2 = 14.1966$
3	Torsional (around ”z” axis)	$\omega_3 = 40.6669$

Regarding to the harmonic analysis, the extraction of the wing vibration amplitudes was configured in a range from 0 to 60 Hz with a resolution of 0.2 Hz, that is, 300 values were collected within this range. The reason for choosing 60 Hz as the upper limit is due to the fact that the wing flexional and torsional frequencies are inside this range (target frequencies), as can be seen at Table 1. Figure 5 shows Frequency Response Function (FRF) of interest of primary structure.

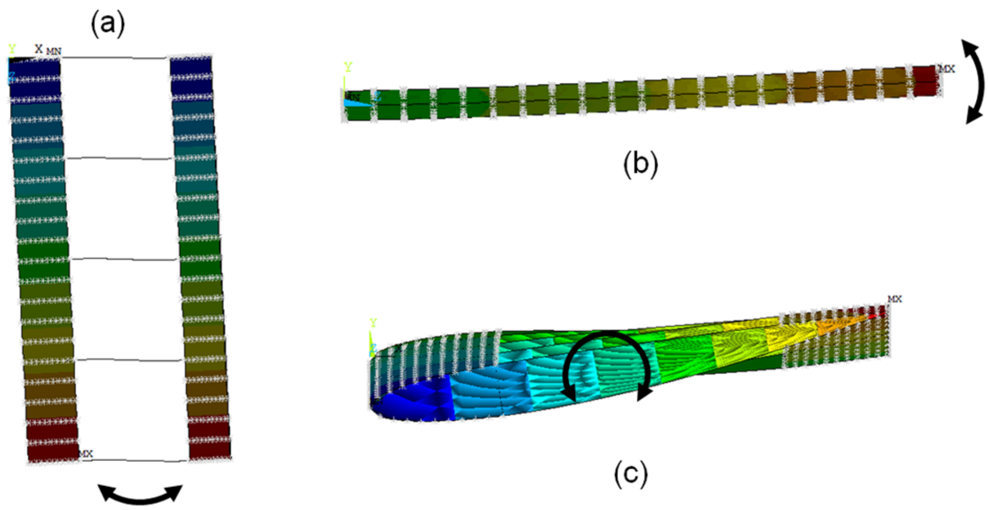

Figure 4. Vibration Modes of Primary Structure: (a) mode 1, (b) mode 2 and (c) mode 3

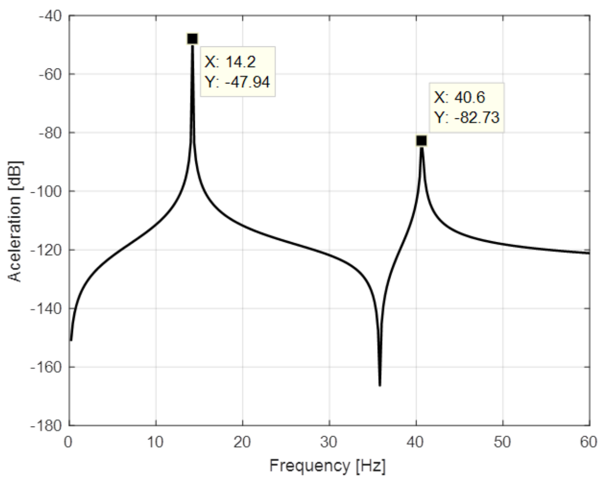

Figure 5. FRF of Primary Structure (wing target frequencies)

4 Design of MMDVA

4.1 MMDVA model and parametrization

This work proposes the use of a MMDVA that need to meet some basic requirements, which are: *(i)* be continuous, *(ii)* simple/easy construction, *(iii)* with not to much parts, *(iv)* that can vibrate in flexion and torsion and *(v)* whose mass does not exceeding 10% the mass of the primary structure. The material used in designing the DVA was isotropic, specifically steel whose properties are: Young Modulus $E = 200GPa$, Poisson ratio $\epsilon = 0.3$ and density $\rho = 7850kg/m^3$. The configuration of the chosen MMDVA is shown in Fig. 6(a). It is composed by two solid steel bars in a " L type" shape with a rectangular section. Its constructive parameters (or design parameters) are the length of the first and second bars L_1 and L_2 and its cross sectional dimensions b_i and h_i with $(i = 1, 2)$.

The numerical modelling of the MMDVA was carried out using the BEAM188 element (with 6 GDL per node). This element is based on Timoshenko's beam theory and used mainly for the design of medium and high length structures. The attachment of the MMDVA to the primary structure is assumed to be a perfect coupling and will be installed to the outer side of the tip wing rib at the leading edge (region with greatest displacements).

A mesh convergence analysis was carried out to determine the number of necessary divisions at each of the bars (number of elements) in such a way that the result of the analysis, in this case, the natural frequencies were not affected by the size of the element, the determined number of elements per bar was ten. The MMDVA mesh is shown in Fig. 6(b).

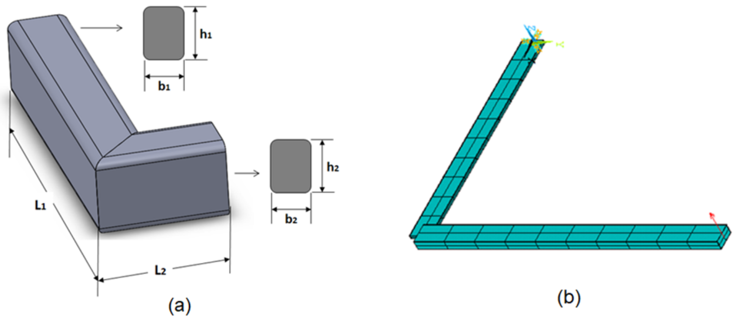

Figure 6. MMDVA model: (a) design parameters, (b) numerical model

4.2 Optimization Process using Genetic Algorithms

As described previously, the N-MMDVA design parameters (L_1, L_2, b_1, h_1, b_2 and h_2, total $N = 6$) need to be strategically modified along an iterative process until a set of these parameters causes two of its natural frequencies coincide or at least approximate, respectively, to the flexural and torsional frequencies of the wing (ω_2 and ω_3 of Table 1). At the present work GAs method is used for this purpose. The GA method consists of a basic principle, that is: the better an individual adapts to his environment, the greater his chance of surviving and generating descendants. GAs work with a population of which these individuals belong. Its adaptability is measured using the value of the objective function.

Initially, a (initial) population is generated composed by a random set of individuals that can be seen as possible solutions to the problem. A percentage of the most adapted are kept, while the others are discarded (Darwinism). The members maintained by the selection can undergo changes in their fundamental characteristics through mutations and crossover or genetic recombination generating descendants for the next generation. This process, called reproduction, is repeated until a satisfactory solution is found. The values used in this work to configure the GA method (using elitism) are the following: crossover fraction $C_f = 0.8$, mutation fraction $M_f = 0.01$, population size $P_s = 12N$ (as recommended in [10]) and number of generations $N_g = 0.8P_s$.

In order to assess whether individuals are well (or poorly) adapted, the objective function (J) represented by eq. (1) was proposed. It computes the absolute difference between the n frequencies to be tuned, in this work two frequencies were chosen: $\omega_1 = 14.1966Hz$ and $\omega_2 = 40.6669Hz$ representing the wing flexional and torsional frequencies and the MMDVA instantaneous frequencies f_i $(i = 1, 2)$ calculated for each set of design parameters (individual), P_s times at each N_g generations. The closer to zero is J, the closer the MMDVA frequencies and the wing are, making it more efficient (basic working principle of DVAs). It is worth noting that each parameter to be optimized was limited by lower and upper bounds. The upper bound of the MMDVA prevents to exceed the maximum mass of the device. The upper bounds are: 0.5 meters for L_i, 0.03 meters for b_i and 0.015 meters for h_i guaranteeing a maximum MMDVA mass of 3.5325 kg (approximately 10.05% of the total wing mass).

$$J = \sum_{i=1}^{n} |f_i - \omega_i| \tag{1}$$

4.3 Results and Analysis

Based on the methodology proposed (shown in Figure 1) and the configuration of the GAs presented before, the optimal parameters of the ”L” type MMDVA were determined. Table 2 presents the results. The mass of the optimal MMDVA was $m_{MDVA} = 0.8974kg$ (Approximately 2.7% of the total mass of the primary structure). The final value of the objective function corresponding to these parameters was $J = 0.0424$. Figure 7 shows the history of the J value corresponding to the best individual over the generations.

Table 2. Optimal MMDVA parameters

Parameter	Value (meters)	Parameter	Value (meters)
L_1	0.45833	b_2	0.0308
L_2	0.28943	h_1	0.00735
b_1	0.0215	h_2	0.0047

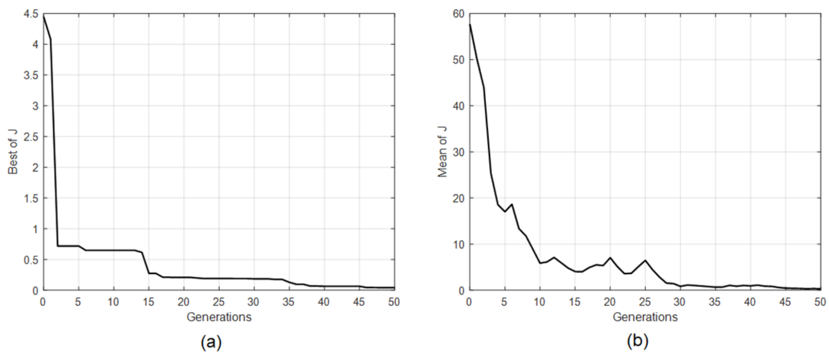

Figure 7. Evolution of the objective function J: (a) Best and (b) Mean

After obtaining the optimal parameters, the efficiency of the optimal MMDVA is verified, for this, the optimal MMDVA was coupled to the wing structure. As mentioned in previous sections, such coupling is performed on the outside of the external wing rib at the leading edge. In Figure 8 it is showed the arrangement of wing+MMDVA.

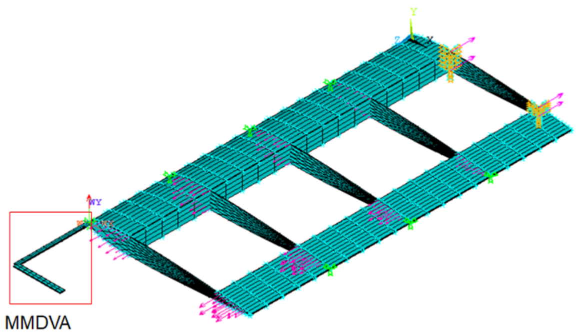

Figure 8. Numerical Model Wing + Optimal MMDVA

To quantify the performance of the designed MMDVA, a harmonic analysis of the set shown in Figure 8 was carried out. The resulting Frequency Response Function (FRF) is shown in Figure 9. It is easy to see the creation of the anti-resonance peaks corresponding to both target frequencies ($\omega_1 = 14.1966Hz$ and $\omega_2 = 40.6669Hz$), the respective frequency bands were 4 and $5.2Hz$. Therefore, it can be said that the methodology for obtaining optimal parameters of the MMDVA was satisfactory applied and good results were obtained.

The main difficulty encountered during the process of determining the optimal MMDVA was to avoid the occurrence of a resulting mode shaped (of the MMDVA) in the ”xz” plane. The oscillation of the MMDVA at that

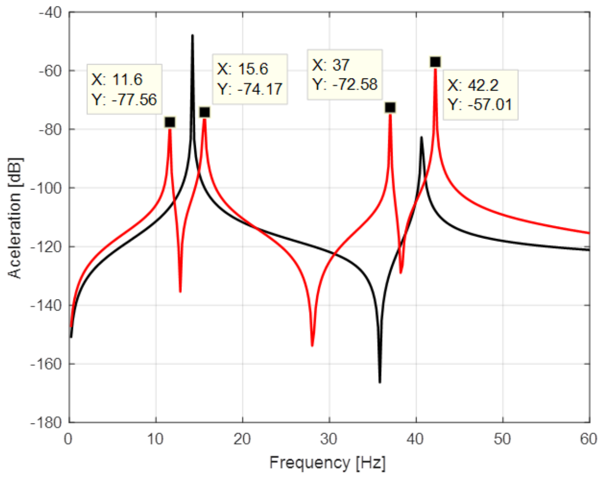

Figure 9. FRF - Wing + Optimal MMDVA

direction makes it inefficient to mitigate vibration in the flexural and torsional frequency. The optimum MMDVA mode shapes are shown at Figure 10. In Fig. 10(a) the vertical oscillation of the optimal MMDVA helped to attenuate the flexural vibration of the wing, the same relationship exists between the mode shape of Fig. 10(b) and torsional vibration mode of the wing.

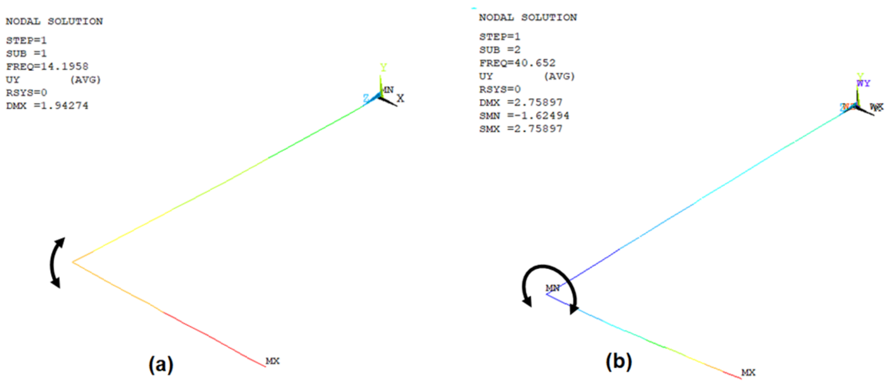

Figure 10. Vibration Modes Shape - Optimal MMDVA

5 Conclusions

A MMDVA for a wing of an aircraft was developed in this work. It was tuned to a finite number of frequencies, specifically the corresponding to the flexional (vertical) and torsional modes. A single MMDVA with only 2.7% of total mass of the primary structure was able to attend the main function it was designed. Results indicate that the applied methodology and GAs optimization method are efficient in the design of MMDVAs and the proposed configuration ("L" type MMDVA). They showed a successfully attenuation of the vibration amplitudes at the predefined wing resonance frequencies with a reasonably bandwidth. In order to improve the results in future works it is worth mentioning that the relatively narrow bandwidth could be amplified if the mass ratio is increased. Another shortcoming is the unavoidable peaks created around the resonance frequencies that could be reduced adding damping to the MMDVA. It is important to highlight that a single difficulty was encountered throughout the work, especially selecting the frequencies of MMDVA to be tuned. To do this, it was necessary to know (and see) the physical shape of the MMDVA vibration modes in order to guarantee that at each of them the direction of the oscillation was able to correctly "excite" the target frequencies of the primary structure. It is highly recommended to study the influence of changing the attachment point of the MMDVA to the wing.

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References

[1] Frahm, H., 1911. Device for damping vibrations of bodies. US Patent 989,958.

[2] Mendez, Y., Cunha, S., Coimbra, R., & Rodriguez, H., 2016. Vibration suppression of a cantilever beam using multi-mode dynamic vibration absorbers. *International Journal of Emerging Technology and Advanced Engineering*, vol. 6, pp. 28–38.

[3] Raze, G., Paknejad, A., Zhao, G., Collette, C., & Kerschen, G., 2020. Multimodal vibration damping using a simplified current blocking shunt circuit. *Journal of Intelligent Material Systems and Structures*, pp. 1045389X20930103.

[4] Zhu, X., Chen, Z., & Jiao, Y., 2018. Optimizations of distributed dynamic vibration absorbers for suppressing vibrations in plates. *Journal of Low Frequency Noise, Vibration and Active Control*, vol. 37, n. 4, pp. 1188–1200.

[5] Debnath, N., Dutta, A., & Deb, S., 2016. Multi-modal passive-vibration control of bridges under general loading-condition. *Procedia Engineering*, vol. 144, pp. 264–273.

[6] Harel, S. S., 2017. *Frequency Tuning of Vibration Absorber Using Topology Optimization*. PhD thesis.

[7] Leung, A. & Zhang, H., 2009. Particle swarm optimization of tuned mass dampers. *Engineering Structures*, vol. 31, n. 3, pp. 715–728.

[8] Diaz Méndez, Y., 2014. *Um Estudo dos Absorvedores Dinâmicos de Vibrações Multimodais*. PhD thesis, Federal University of Itajubá, Brazil.

[9] Venkatesan, S., Beemkumar, N., Jayaprabakar, J., & Kadiresh, P., 2018. Modelling and analysis of aircraft wing with and without winglet. *International Journal of Ambient Energy*, pp. 1–11.

[10] Ayad, A., Awad, H., & Yassin, A., 2013. Parametric analysis for genetic algorithms handling parameters. *Alexandria Engineering Journal*, vol. 52, n. 1, pp. 99–111.