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A new tool to understand, evaluate and optimize vibro-acoustic solutions with Dynamic Vibration Absorber (DVA)

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ABSTRACT

The present paper describes a new predictive tool called "SDFEM" (Sener Dynamic Force Equivalent Method), used to evaluate noise and vibration countermeasures and optimize relevant design parameters of these solutions. In particular, optimal distributions of Dynamic Vibration Absorbers (DVA) on complex structures are investigated, providing new insights towards the design and efficiency of these vibro-acoustic countermeasures.

The theoretical background, the development and the validation of the SDFEM tool are briefly presented. SDFEM is based on the Dynamic Force Equivalent Method, Finite Elements Method and an effective integration with MATLAB. The key advantage of the SDFEM tool and methodology is the ability to estimate vibro-acoustic responses of countermeasures configurations in only few milliseconds.

With the help of the SDFEM tool, large numbers of countermeasures configurations can be evaluated. In particular, tendencies regarding vibro-acoustic reductions based on distribution, weight, tuned mass, tuned frequency and damping can be easily assessed. A genetic optimizer algorithm is although implemented in the SDFEM tool in order to identify the optimized sets of countermeasures. To demonstrate the use of the SDFEM tool, fundamental tendencies of DVA designs for simple elements (cantilever beam) as well as advanced sensitivity analysis of DVAs for complex structure (aircraft) are presented.

Keywords: Vibro-acoustics, Optimisation, DVA
I-INCE Classification of Subject Number: 76

1. INTRODUCTION

The extensive use of CAE (Computer Aided Engineering) has played a fundamental role in designing structures with low vibro-acoustic impact. In particular, predictive models offer the means to evaluate, analyse and understand vibro-acoustic countermeasures applied to more complex structures. While computational resources are constantly increasing and allow for more complex models, vibro-acoustic predictive model still faces limitations regarding computational costs. In particular, optimisation process of countermeasures, which requires the prediction of a large number of configurations, are limited by computational costs when applied to complex structures.

The SDFEM tool (Sener Dynamic Force Equivalent Method) has been developed in order to tackle the previously identified limitation. In particular, the first stage of the

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SDFEM tool focuses on Dynamic Vibration Absorber (DVA) countermeasures, also known as Tuned Vibration Absorber (TVA), Tuned Mass Damper (TMD), harmonic absorber or seismic damper. The main objective of SDFEM is to offer a fast and reliable way of evaluating large number of countermeasures configurations, and display the results for advanced analysis of tendencies and optimisation. This objective is reached by applying an already well-known methodology, which implies the use of dynamic forces to represent the effect of the countermeasures. The integration of this methodology with Finite Element models (FE models) and optimisation algorithm, performed under the MATLAB environment, offers a fast and reliable solution, which makes it applicable to complex structures with existing FE models.

The present paper briefly describes the identified state of the art in terms of vibro-acoustic countermeasures optimization, followed by the theoretical background of the SDFEM tool, emphasizing the requirements of using such a tool in an industrial environment. Validation results are then presented, and predictive results of more complex structures are then discussed, demonstrating the potential of the SDFEM tool as an analysis and optimization tool for complex vibro-acoustic systems.

2. STATE OF THE ART AND REQUIREMENTS

Taking into account that vibration control is a key aspect in many engineering fields, several research and development are performed by investigation teams and private corporations. Those investigations usually focus on improvement of vibration behaviour of structures in the last stages of its design. In particular, the aerospace industry is aiming for an improvement in weight and functionality of the aircraft structures by optimizing their vibration response.

Benefiting from the progressive increase of computational power, companies and research groups are focusing on numerical methods for vibration optimization, rather than trial and error and expert guessing. The Spanish companies SENER Ingeniería and SENER Aerospace participate in the development of formulation, simulation and testing of optimization methods for vibration countermeasures, such as the ones seen in [1], [2], [3], [4] and [5].

Among the relevant available literature, it was identified that efforts have been directed towards the improvement of DVA architecture in order to avoid internal resonance [6], or to completely redesign the architecture of a DVA [7]. Other studies focus on an in-depth study of the effect of a single DVA in a large scale of frequencies, evaluating the importance of each of the characteristic parameters of the device [8].

Complementary approaches consist on the development of optimization methods with genetic algorithms focusing on parameters of active vibration control [9], while other studies apply Non Nominated Genetic Algorithms to optimize the characteristics of the DVAs [10]. In particular, results presented in [5] demonstrated the need for practical sensitivity analysis in order to avoid optimal solution with ineffective extra weight: by using half of the total weight of the countermeasures, differences in vibrations were estimated to be less than 5% in amplitude.

A relevant analysis of DVA can be found in the work performed by Den Hartog [12]. It is worth mentioning that the SDFEM tool will be used, as a future step, to evaluate relevant results obtained by Den Hartog in the analysis of the damping effect of DVA. Nevertheless, the present analysis offers a different approach to the theoretical background assessed by the research presented in [12]. In particular, this is observed taking into account that the optimization process of the SDFEM toolbox is based on results from a large number of simulations in comparison with finding the optimum results from a mathematical point of view derived from the equations of motion.

Insights gained by performing the literature review, in addition to the industrial needs identified while developing vibro-acoustic countermeasures with DVAs, have pinpointed the requirements of an effective predictive tool such as the SDFEM tool:

- Multi objective optimization of solution based on device parameters (weight, stiffness and damping), positions (location of devices on the structure) and vibro-acoustic objective (average of vibration or noise, max value, multi frequency, etc).
- Comprehensive sensitivity analysis based on optimization results: prevent increasing the total weight of solution if it leads to limited improvements.
- Possibility to define countermeasures catalogue based on available devices, and perform transversal optimization.
- Perform countermeasures optimization at advanced stage of the design, taking advantage of the existing FE models used at the early stages of the design.
- Allow “brute-force methods” to be implemented, offering a complete insight of all the possible solutions.

3. THEORETICAL BACKGROUND

3.1 Vibration analysis. Dynamic Vibration Absorber

Within the framework of structural mechanics, the general movement equation of a system with multiple degrees of freedom is written as:

$$\boldsymbol{M}\ddot{x} + \boldsymbol{C}\dot{x} + \boldsymbol{K}x = F(t) \qquad (1)$$

Where mass matrix M, stiffness matrix K, damping matrix C, dynamic loads vector F(t) and position vector x(t) are identified. When harmonic loads $F(t) = F_0 e^{i\omega t}$ are applied, the solution of such equation is defined by $x(t) = Xe^{i\omega t}$, where the complex vector of amplitudes X is determined by:

$$X = [\boldsymbol{K} + i\omega\boldsymbol{C} - \omega^2\boldsymbol{M}]^{-1}F_0 \longrightarrow X = \boldsymbol{H}F \qquad (2)$$

Where the unitary displacement matrix H is identified. The Dynamic Vibration Absorber is modelled as a damped spring-mass system. When attached to the main structure, the general movement equation of the entire system becomes:

$$\begin{bmatrix} m & 0 \\ 0 & m_a \end{bmatrix}\begin{bmatrix} \ddot{x} \\ \ddot{x}_a \end{bmatrix} + \begin{bmatrix} c + c_a & -c_a \\ -c_a & c_a \end{bmatrix}\begin{bmatrix} \dot{x} \\ \dot{x}_a \end{bmatrix} + \begin{bmatrix} k + k_a & -k_a \\ -k_a & k_a \end{bmatrix}\begin{bmatrix} x \\ x_a \end{bmatrix} = \begin{bmatrix} F_0 e^{i\omega t} \\ 0 \end{bmatrix} \qquad (3)$$

The effect of the DVA on the main structure is observed after obtaining the vector of amplitudes X from the previous equation:

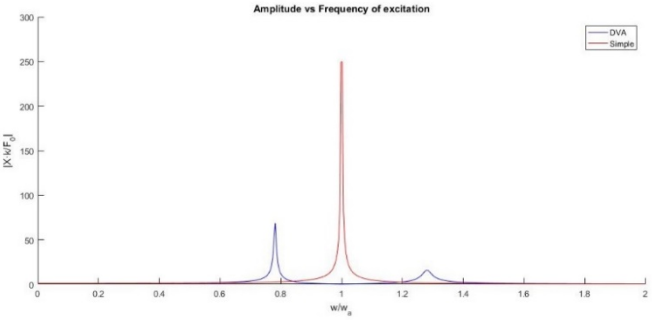

Figure 1. Comparison of main structure amplitude with and without DVA.

3.2 Dynamic force equivalent method

The root of the SDFEM tool is the use of the dynamic force equivalent method, whose theoretical background is detailed in [11] and [1]. It can be synthetized as follows:

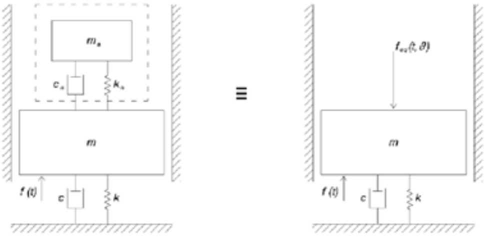

Figure 2. Scheme of the dynamic equivalent force method for a single DVA.

From a theoretical point of view, the use of the dynamic force equivalent method offers a fundamental advantage. By simplifying the effect of DVA to a dynamic force, numerous forces can be applied to the baseline FE model of the original structure, hence the effects of all DVAs can be estimated in a fast way by applying linear superposition of individual forces to the FE model. For each point of the FE model where the dynamic force is applied, hypothesis of linear mechanical model are applied. This implies that the total movement of a given point is the linear sum of the initial displacement with the corresponding displacement due to the dynamic force.

The key aspects in this method is the estimation of the equivalent dynamic force, which depends on the following parameters:

- Mass, stiffness, damping of the DVA
- Position of the DVA
- Position and properties of all other DVAs present in the solution
- Position and amplitude of the excitation of the baseline model
- Initial calculation of the vibro-acoustic parameters of the baseline model.

Using the movement equations of DVA attached to the main structure, the equivalent force per each device i, as well as the general vector of equivalent forces, are defined:

$$f_i^{eq} = \omega^2 \frac{m_i^a(k_i^a + i\omega c_i^a)}{k_i^a + i\omega c_i^a - \omega^2 m_i^a} X_i \longrightarrow F^{eq} = \boldsymbol{a}X \qquad (4)$$

Going back to equation (1), the vector of total forces is assumed to be the sum of external loads and DVA equivalent forces (lineal mechanics hypothesis), $F = F_0 + F^{eq}$. Hence, combining equations (1) and (4), the general movement equation becomes:

$$(\boldsymbol{I} - \boldsymbol{Ha})X = X_0 \qquad (5)$$

Which is a linear equation, dependant of H, a and the vector of amplitudes due to external loads X_0. To obtain the amplitude of the main structure, the previous equations system is solved by using the Cramer method. This method offers a fast and efficient way to solve the system, making it ideal to develop in a code such as MATLAB.

3.3 Finite element baseline model

Another fundamental aspect of SDFEM tool is the use of an existing Finite Element (FE) model, referred to as the "baseline" FE model. This model is used to obtain the initial displacement of the baseline structure and to obtain the unitary displacement matrix between countermeasure application points and the points of interests (output points) for the optimization process. The use of a baseline FE model was identified as a key requirement for the tool in order to easily be used with existing projects where ongoing FE simulations were performed, without the necessity of modifying the baseline model.

At present, the SDFEM tool has been developed in order to be used in conjunction with MSC NASTRAN for FE models. After importing the baseline FE model, the SDFEM tool will generate the MSC NASTRAN header for the calculation of the unitary displacement matrix, based on the proposed countermeasure positions and output points.

4. VALIDATION OF THE METHODOLOGY

The validation of SDFEM is performed with a cantilever beam. Results from SDFEM are compared with numerical simulation and experimental testing.

4.1 Numerical validation

A cantilever beam (Figure 4) is submitted to a harmonic vertical load on its free end, whose frequency equals the first mode. This study aims to obtain an optimal distribution of DVA using SDFEM, and validate such results by means of the numerical simulation of the solution. A FE model of the beam is created.

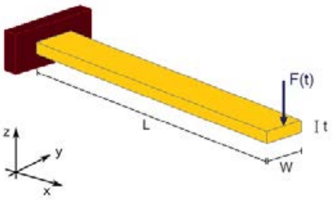

Figure 3. Cantilever beam submitted to a harmonic vertical load on its free node.

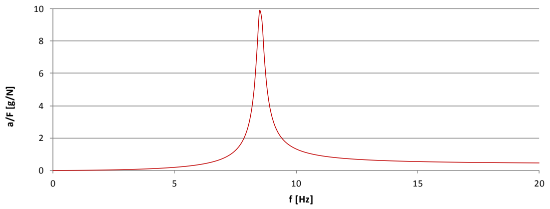

Figure 4. Frequency response of the cantilever beam.

The previous figure represents the frequency response of the beam at the free end. The frequency of the harmonic excitation is set to the normal mode, fe = f_1, located at f_1 = 8.5Hz, in order to study the resonance state of the structure. An optimal distribution of DVA is to be found with SDFEM tool. The following inputs are defined:

- Countermeasure points. A total of 8 points, located along the transversal beam axis at x-position n·L/10 (for n = 1 to 8), are proposed.
- DVA Catalogue. One type of DVA is proposed, with m_a = 58g and f_a = 8.5Hz and

After executing SDFEM, the best distribution of devices provided by the tool has the following characteristics:

- DVA located at x = 8L/10 (closest possible position to the free end).
- Reduction of 98.4% with respect to original vibrations.

Such solution is numerically modelled by adding a mass-stiffness-damper element to the initial FE model, as determined by SDFEM. Its frequency response is presented:

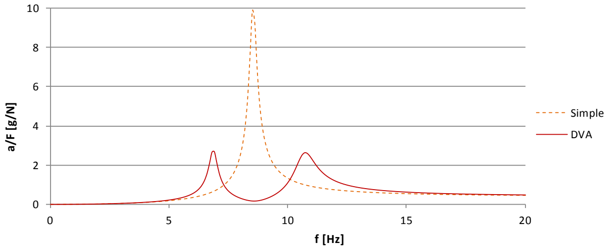

Figure 5. Frequency response of the cantilever beam with attached DVA.

Particularly, at f_e = 8.5 Hz, the reduction achieved with the application of DVA equals 98.3%, a slight deviation of 0.1% compared with the value provided by SDFEM tool. Results obtained with SDFEM can be considered valid for this simple case.

4.2 Experimental validation

The previous scenario, shown in Figure 4, is set up and tested in order to validate experimentally the results given by SDFEM tool. The harmonic force is generated by an electric motor assembled near the free end with an eccentric mass coupled in its axis, whereas the acceleration of the free end is measured by an accelerometer.

The Figure 7 compares the frequency response of the structure submitted to a harmonic force at frequency f_e = 8.5 Hz, with and without DVA attached to its position x = 8L/10.

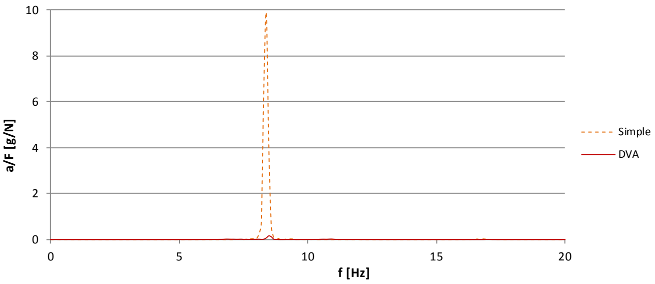

Figure 6. Frequency response of the cantilever beam with attached DVA.

At this frequency, the new amplitude is observed to be much lower with the vibration absorber. Particularly, the reduction achieved with the application of DVA equals 98.7%. Such results presents a slight deviation lower than 0.3% compared with the value provided by SDFEM tool. Accordingly, it can be stated that results obtained with SDFEM, with the FE model and the experimental setup offer a high level of correlation, validating the SDFEM tool for a simple element.

5. DVA DESIGN STRATEGIES ON CANTILEVER BEAM

While performing the validation activities of the SDFEM tool with the cantilever beam, a relevant approach for the design of the DVA solution was identified: the tuned frequency of the DVA can be set in order to fit the excitation frequency or it can be set to fit the most relevant mode. Both methods will respectively be referred to as “Source killer” and “Mode killer” and will be discussed in this chapter. When under a single dynamic load at a given frequency, literature reviews shows that tuning the DVA at the excitation frequency is generally the best solution, while under loads over a wide frequency range, designing DVA at given structural modes lead to overall better results.

5.1 Source “Killer”

As a first approach, a typical design method for DVA consists in tuning its frequency to the excitation frequency of the vibrating structure (“Source Killer”). The object case consists of a cantilever beam, with first longitudinal modes at 16Hz and 100Hz, subjected to a vertical harmonic force at 50Hz located at x = 2L/3 from the embedded section.

Among the various DVA design parameters, emphasis was given in evaluating the effect of its individual mass, either considering the sum of all DVAs mass as a fixed parameter or observing the effect of individual DVAs. In this case, a total mass of DVAs of 40g was considered, corresponding to 20% of the complete beam mass. 20 DVA types were considered, with moving mass ranging from 40g down to 2g. For each configuration, the SDFEM toolbox finds the distribution of DVAs that leads to the best solution in terms of vibration reduction ratio. All calculations were performed in less than 10s.

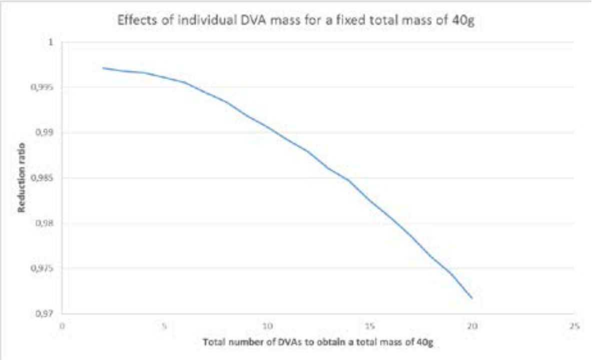

Figure 7. Effects of individual DVA mass for a fixed total mass of 40g.

Results presented in the previous graph clearly show that, for a total mass of 40g, the reduction ratio is higher for solution with less DVAs but higher DVA individual mass.

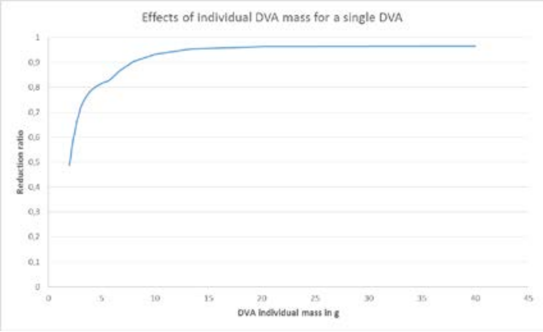

Figure 8. Effects of individual DVA mass for a single DVA.

Results of previous graph show that, when only one DVA is installed, higher mass lead to higher reduction ratio. All the results were obtained with a computational time of less than 5s. The figure also shows that the increase of reduction ratio is limited for DVA mass higher than 15g. This is one of the main goal for the SDFEM toolbox: offer additional sensitivity regarding behaviour of DVA and evaluate results not only based on the absolute reduction value, but introduce tendency curves that will help the engineer choose a solution with the best compromise between reduction and weight.

5.2 Mode “Killer”

As an alternative approach, a design method for DVA consists in tuning its frequency to the closest natural frequency of the structure. This approach is referred as the “mode killer” in the present study. The excitation of the beam will consist of a dynamic load at a given frequency range. The object case consists of a cantilever beam, whose first longitudinal mode is 16Hz, and is subjected to a vertical load with a frequency excitation ranging from 12Hz up to 20Hz, located at x = 2L/3 from the embedded section. The excitation frequency range include the first normal mode of the beam (16Hz).

As for the previous analysis, emphasis was given in evaluating the effect of individual DVA mass, considering the sum of all DVAs mass as a fixed parameter, and observe the effect of individual DVAs. A total mass of DVAs of 40g was considered, (20% of the total mass of the beam). A total of 20 DVA types were considered, with moving mass ranging from 40g down to 2g. For each configuration, the SDFEM toolbox finds the geometrical distribution of DVAs that leads to the best solution in terms of vibration reduction ratio. In this case, such ratio considers the sum of all accelerations within the indicated spectral range. All calculations were performed in less than 300s.

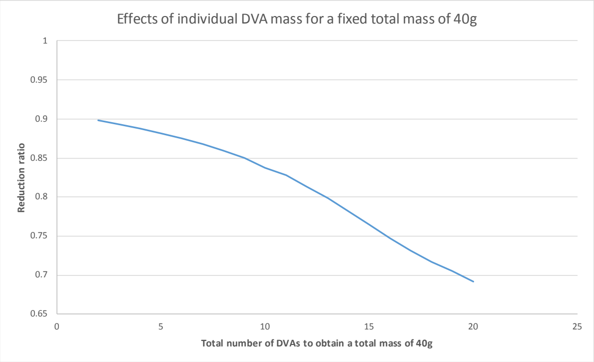

Figure 9. Effects of individual DVA mass for a fixed total mass of 40g.

Similar to what was observed in the previous analysis (source killer), results presented in the previous graph clearly show that, for a total DVA mass of 40g, the reduction ratio is higher for solutions with less DVAs and higher mass per DVA. The following figure compares the best distributions of DVA for both source and mode killer

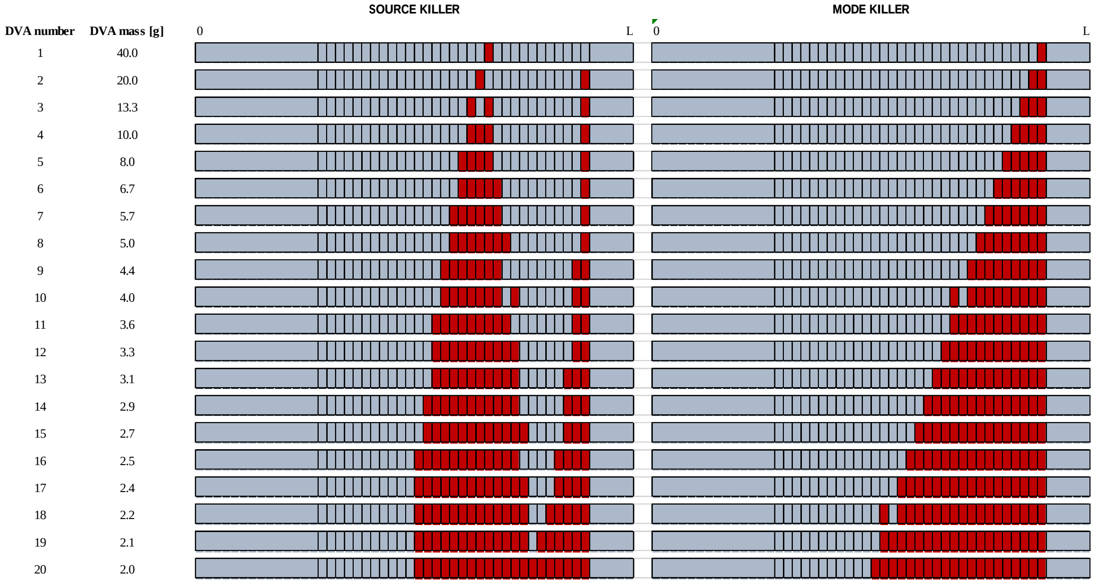

Figure 10. DVA Distribution on the beam for Source (left) and Mode Killer (right).

For "Source Killer", as the number of DVA increases, best solutions are obtained by means of locating such devices around both x=2L/3 (where the harmonic load is applied) and the free node (where maximum displacement takes place). Such result is different to what is observed in the "Mode Killer", which provides its best solutions by locating DVAs around the free node.

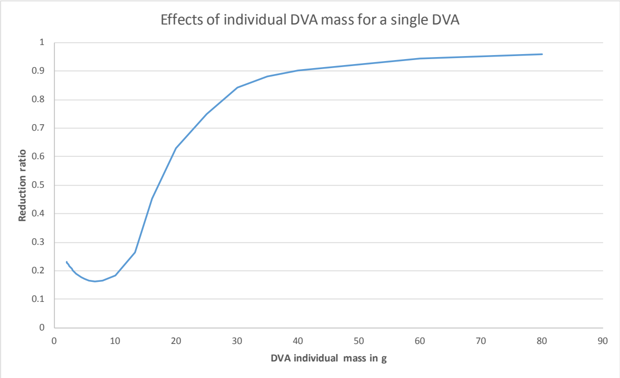

Figure 11. Effects of individual DVA mass for a single DVA.

Results presented in the previous graph show that, when only one DVA is installed, higher mass lead to higher reduction ratio. The tendency in terms of reduction ratio tends to stabilise after a given mass value (in this case, above 40g). This result is fundamental as it changed the conclusions reached in the “Source Killer” analysis, where a DVA mass higher than 15g did not lead to a sensible ratio increment. The SDFEM tools gave the opportunity to understand that, in the “Mode Killer” design configuration, higher DVA individual mass is the objective. It is also worth observing that individual DVA mass of 5g or 10g lead to inferior reduction ratio when compared to a DVA mass of 2g. All calculations were performed in less than 180s, which is higher than the previous analysis due to the fact that response at 40 frequencies between 12Hz and 20Hz were calculated.

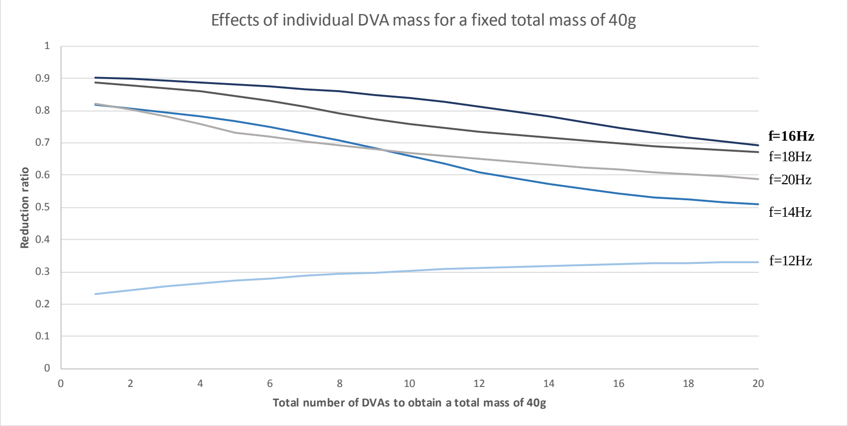

Figure 12. Effect of DVA tuned at different frequencies for a fixed total mass of 40g.

Results presented in the previous figure show that tuning the DVA towards the normal mode of the structure offers the highest reduction ratio. It is worth commenting that DVAs tuned at frequencies above the normal mode frequency provide better results than when tuned at frequencies below such frequency.

An additional design strategy for the DVAs consists in installing various DVAs tuned at various frequencies. The SDFEM tool offers the possibility to combine DVAs tuned at different frequencies and evaluate the results:

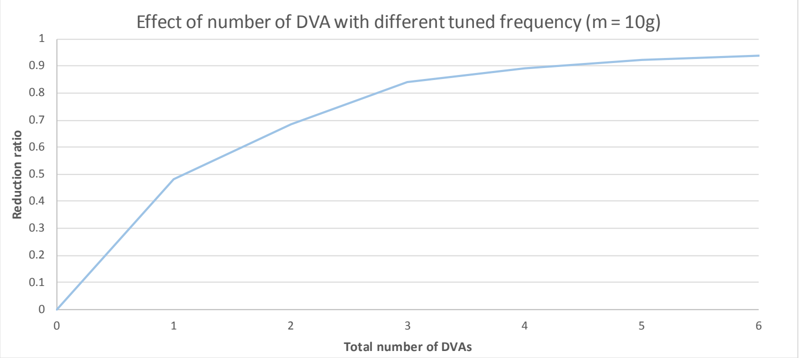

Figure 13. Effect of number of DVA tuned at different frequencies.

In each case, the best distribution has combined different DVA types, with similar moving mass (10g) but tuned at different frequencies. The results from previous figure show that, when a structure is submitted to a harmonic load over a given spectral range, optimized reduction ratios can be obtained with various DVA tuned at different frequencies. Additionally, it can be observed that the reduction curve stabilize for solutions with more than 4 DVAs. To synthetize the previous analysis, the following table shows an overview of some relevant results considering a total mass of solution of 40g:

Table 1. Reduction ratio of different configurations with total mass of 40g.

Number of DVAs	Individual Mass	Tuned frequency of DVA	Total mass of solution	Reduction Ratio
1	40g	16Hz (Mode Killer)	40g	0,9
2	20g	16Hz (Mode Killer)	40g	0,9
4	10g	16Hz (Mode Killer)	40g	0,89
1	40g	18Hz	40g	0,89
1	40g	14Hz	40g	0,81
4	10g	14Hz, 16Hz, 17Hz, 18Hz	40g	0,89

It can be concluded from the previous table that a number of different DVA design strategies can be followed in order to obtain an optimized reduction ratio of vibration with a total mass of the solution of 40g. The use of a single DVA of 40g in the "Mode Killer" configuration only offers marginal increase of reduction ratio (1%) when compared to a solution of distributed DVAs of 10g tuned at various frequencies. Additionally, it was observed that a single DVA of 40g tuned at 18Hz (2Hz above the natural frequency of the beam) could lead to similar reduction ratio, while it can lead to inferior results (9% lower in terms of reduction ratio) when tuned at 14Hz. The comparison of all these results is made possible by the capability of the SDFEM tool to quickly assess and optimize DVA configurations with a large number of variables.

6. APPLICATION OF SDFEM TO COMPLEX STRUCTURES

In order to further demonstrate the use of the SDFEM toolbox, an application case based on a complex structure is described: an aircraft wing from a turboprop aircraft.

It was considered that the turboprop engine presents balancing problems due to a deviation in the propeller-axis coupling, generating a harmonic load transmitted to the wing. The range of load frequencies (32.2Hz to 36.2Hz) corresponds to the blade passing frequency (BPF) of the aircraft. The second longitudinal mode of the wing (34.2Hz) is included within the frequency range of the blade passing frequency.

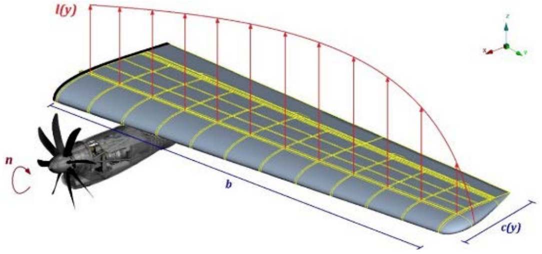

Figure 14. Aircraft wing submitted to turboprop vibrations.

In this application case, emphasis was given in evaluating the effect of both individual DVA mass and tuned frequency, as well as providing a general compromise solution attending to the required total mass and number of DVA.

A total of 35 DVA types were considered, covering a DVA mass ranging from 0.5kg (0.5% of the total wing mass) to 3kg (3%) and a frequency range from 32.2Hz to 36.2Hz. For each configuration, the effect of a single DVA is also evaluated. The SDFEM toolbox identifies the geometrical distribution of DVAs that leads to the best solution in terms of vibration reduction ratio. As previously indicated, such ratio considers the sum of all accelerations within the indicated spectral range.

Results are shown in the following graph, presenting tendencies in terms of reduction ratio for various DVA mass and DVA frequency:

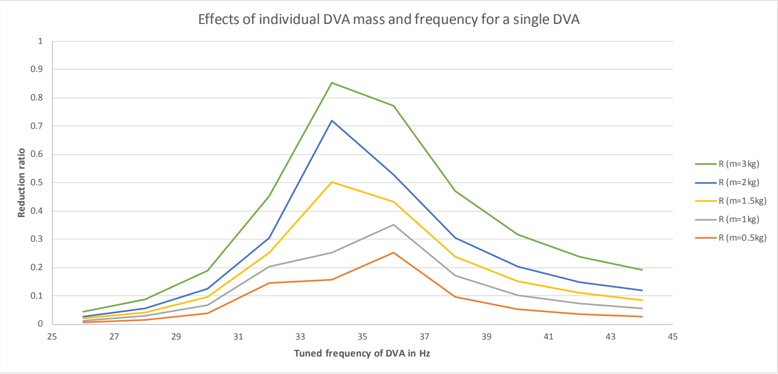

Figure 15. Effect of individual DVA mass and frequency for a single DVA.

The previous figure clearly shows the influence of mass and frequency on DVA behaviour. Similar to the previous cantilever beam analysis, the reduction ratio is improved by increasing the DVA mass. Generally, tuned frequencies close to the wing mode provides better results, nevertheless, it is worth mentioning that for lowest masses (1kg and 0.5kg) the best performance is obtained for DVAs tuned at 36Hz. This last results clearly shows the advantage of using the SDFEM tools when facing a DVA design strategy based on a catalogue of available DVAs.

After analysing the individual effect of each DVA, a second calculation is performed in order to obtain distributions of combined DVAs for different number of devices, evaluating the required total mass for each one.

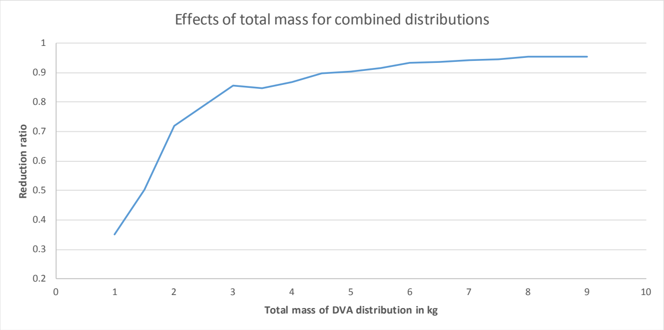

Figure 16. Effect of total mass for combined distributions.

The previous plot clearly shows that the reduction ratio is only slightly increasing for solutions with a total mass higher than 6kg. Hence, for this particular application case, a relevant compromise solution would be to implement a DVA solution with a total mass of 6kg, providing a reduction ratio of 0.93 and assuming an increment of 6% the total wing mass. For this particular solutions, there is a total of 3 DVAs with mass of 1kg, 2kg and 3kg, and tuning frequencies of 34Hz, 36Hz, 34Hz. This DVA solution could be identified with the help of the SDFEM toolbox and demonstrates its effectiveness for more complex structure when a compromise solution is required. In particular a weight reduction of 3kg is obtained (from 9kg to 6kg, reduction of 33%) while the reduction ratio is only decreased by 0.02 (0.95 vs 0.93, reduction of 2%).

7. CONCLUSIONS

The present conference paper presents the SDFEM tool as a new tool developed in order to tackle the limitations related to computational cost of predictive models. Focusing on vibro-acoustic solutions such as DVA, the SDFEM tool offers a fast and reliable way of evaluating large number of countermeasures configurations, and display the results for advanced analysis of tendencies and optimisation.

Following a preliminary theoretical background for the new tool, validation of the SFEM results is presented for a simple cantilever beam, comparing results with numerical (FE) solutions and experimental data. Results demonstrate that the SDFEM predictions are within acceptable range of correlations with the FE and experimental data.

Results of applying the SDFEM tool to a cantilever beam under different dynamic loads have demonstrated a new insight regarding DVA behaviour with a very limited computational cost. In particular, relevant data regarding design methodologies of DVA (Source/Mode killer) was briefly presented. Those preliminary results applied to a simple structural element show that the SDFEM tool is a fundamental tool to help engineers design effective DVA solutions.

Finally, SDFEM tool is applied to an application case, concretely an aircraft wing. Its implementation has allowed to analyse the effect of different DVA design parameters on this particular structure and to obtain a compromise solution attending to engineering criteria, such as maximum added mass. Compared to the best solution available, a compromised solution was found with a weight reduction of 33% (9kg to 6kg) and a reduction ratio only decreased by 2% (0.95 to 0.93). The SDFEM toolbox has demonstrated its effectiveness as a design tool for DVA solutions in a complex structure.

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