Design of A Ground Vibration Test Certification System For Unmanned Air Vehicles

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Abstract

From the last decades a trend was created how defining every aspect of the structures surrounding us. We need to predict their behaviour in every situation so that we can have a safer and trustworthy human environment. One important aspect that is always present is the structural integrity of what we build. In a more specific approach to the problem we can analyse the way structures vibrate. In aircrafts, this problem stands with an even bigger impact. There is a need to have more reliable aircrafts that can handle all types of vibrations and there is a continuous study of these aspects. In order to do that, experimental modal analysis has been a very important part of the certification process of aircrafts. It allows to validate and update the computational models needed in order to have flight clearance and to perform the aircrafts final structural and aeroelastic analysis. In this thesis, ground vibration tests were performed on a small UAV in order to acquire critical modal data for the updating of finite element models. It was used impact testing and shaker testing, on two different wing sets, for flight clearance purposes for both cases. It is the purpose of this work to present the process and the results of such tests, evaluating at the same time if these procedures can be applied not only to linear structures but also to ones that present non-linear behaviours.
Keywords: Experimental Modal Analysis, Ground Vibration Testing, Finite Element Model Updating, Modal Testing, Modal Parameter Estimation

1. Introduction

Nowadays, the established concept of designing an aircraft is based on heavy computational analysis, relying in mainly computer models to predict and dictate the future performance in an aircraft, specially when it comes to structural analysis. The use of experimental testing is not usually seen has an important factor in this process, and this thesis has purpose to change that point of view. Experimental testing plays a vital role in the design process, particularly when it is used in collaboration with the analytical processes. It allows to gather data about the real dynamics of structures and it can be used to validate, and if needed, update the models that are relied upon for structural and aeroelastic analysis. This work is included on a major project ordered by Embraer S.A. to the Center of Aerospace Research of the University of Victoria where it was developed. The main purpose of the project is to study and observe coupling between structural modes in the wing and the aerodynamic modes in a UAV aircraft, denominated in the project as QT1. For that the 1^{st} bending mode is very important and will have a special attention given to it. My work is part of the project by performing the necessary experimental modal analysis of the UAV created for the purpose of this project and the update of the finite element models for further structural and aeroelastic analysis for among other studies, flight clearance as well.

2. Background

GVT, as any other experimental work, has its own unique set of instruments and tools for data acquisition. There are plenty of options in the market for GVT testing, but in the end, the final choice is made taken into consideration the object under study and the budget if the project itself. For the instrumentation of the testing we can have it classified into different groups:

- Excitation Source
- Response Measurement System
- Data Collection System

When it comes to excitation sources, there are two major techniques that are used: Impact testing and Shaker testing.

2.1. Impact Testing

Impact testing is a very simple procedure that consists on hitting the test object with an impact hammer. This impact hammer resembles an ordinary hammer with the slight difference that, on its tip, it has an impedance head that will measure the force input into the test object, that will later be sent to the Data Collection System. The impacts are done by a technician and so, the results may vary from technician to technician and by his/her technique. The hammer should be impacted in a 90°angle in relation to the objects surface. The force input should be the same for each impact and its value is usually decided by the technician taking into consideration the test object and its material. In order to be able to acquire good results for different objects and materials there are different tips available from where one can be selected that better suits a particular case, from supersoft to hard tips.

2.2. Shaker Testing

Shaker testing implies the use of a shaker to excite the test object or system and this method is more versatile than the impact testing because the excitation from the shaker can be modelled electronically by the user and thus guaranteeing that the excitation input into the object is always the same throughout the test, what cannot be said for the impact testing since it is humanly operated. In this work, the term shaker is used to refer to the whole excitation source in which the shaker is included, but the shaker system is not only composed by the shaker. This system is composed firstly, and obviously, by the shaker; the stinger, a long connecting rod, that will attach the shaker to the structure; cabling and lastly the impedance head, or force sensor. This impedance head, in this case a PCB Shock ICP model 288D01,is a very sensitive device that allows to measure the force input into the system or the acceleration at the point of installation. The second feature is that, since it can also work as an accelerometer, it is used as checking system while doing the installation. Reciprocity tests have to me made before the beginning of the testing to guarantee that the shaker is well connected. Otherwise, errors could be input into the measurements and all the work made while testing is lost.

3. State of The Art

The **standard way of testing** for the past decades has been, for large aircrafts, the **phase-resonance method**, or the commonly called **normal mode testing** [2] [3]. This method is very appealing for this application because it is capable of doing a separation of closely spaced modes.

Normal mode testing consists on doing a single sine excitation at the natural frequencies of the modes. With a proper choice of shaker position and the phase relation between the sine excitation signals, the aircraft will be forced to move as a single-degree-of-freedom system, and the vibration response will only contain a contribution from the mode of interest.

This method presents various advantages:

- The real modes of the corresponding undamped structure are directly measured.
- All eigenvectors are excited at a high energy level.
- Linearity tests can be easily performed.

But it has one main disadvantage that is the testing time. Unfortunately it is a very time consuming method and usually, to cover for that, it is complemented and sometimes partially substituted by phase separation techniques.

These techniques will determine the aircraft modes by evaluating its FRF and so what happens is that the majority of modes will be determined by these "side-techniques" but the the most important modes are still based on normal mode testing.

The modes determined by the normal mode testing are called **critical modes** and they are considered critical if they [4]:

- Significantly differ from the predictions
- Show non-linear behaviour
- Are important for flutter calculations

In the meanwhile, further technological breakthroughs have been happening and some new techniques have grown and proven to be able to produce good results.

In the case of the partners French ONERA and the German DLR [1] it is being used a **combinations of PSM and PRM making use of the individual advantages of the two methods**.

Another new approaches are in the field of Spatial-Optical Approaches. There are several approaches to non-contact image or laser vibration response measurement systems that could lead to an higher spatial resolution without the time and labour cost of installing hundreds of accelerometers as it happens with the conventional GVT methods. Following, the new relevant methods are listed:

- Photogrammetry, using:
  - Camera Photogrammetry Systems
  - Photogrammetric Digitizers
- Projected Dot Videogrammetry
- Laser measurements, using Laser Doppler Vibrometers

4. Implementation

4.1. Finite Element Models

The finite element model serves as the basis for all the testing that was perform and also for further analysis, thus the need for verification validation and updating of this model.

This model will be used to perform structural analysis in Nastran and serve as basis for the aerodynamic analysis update as well.

From the completed Finite Element modes we can have the basis for the estimations of the results that can be found while performing GVT. This values are very important to have, if possible, before the GVT because the instrumentation decisions can be done beforehand and prevent situations were modes cannot be measured because of unfundamented decisions.

This results allow to have a better choice of hardware as:

- The shaker system that can excite in the frequencies of interest;
- Data collection systems, and their resolution and accuracy;
- Support systems without resonance modes close to the modes of the aircraft.

But in the end, these results prove very useful to provide a better first feeling if the results obtained from the GVT are any close to them. If great disparities are found, it could mean that one of the two is probably wrong, but its always given priority to the GVT results.

Another advantage taken from this model is that optimal excitation positions can be simulated and determined in order to guarantee that a good excitation of the set of modes required for model updating of the complete aircraft structure.

4.2. GVT Results

The QT1 aircraft has two wing configurations to be tested: one is a conventional rigid wing and a so called “flexible wing” where the inboard part of the wing is made of an less stiffer aluminium spar .

The format of these two wings is exactly the same, so that the existing FE model has the same basis for both cases, only different structural properties that have to do with the inboard parts of the wings, that were built differently.

The two configurations were tested in order to update the existing finite element models so that they can be used for aerodynamic and aeroelastic analysis so that the QT1 can be flight cleared. For that reason, a tight schedule was imposed and a very long series of test were done in a very short time span.

Over 200 hours of testing were spent with testing, with the various configurations and testing parameters. The results that are going to be presented only show a small part of the work put into the testing, since all those hours can be briefly resumed into a couple of result tables. I insert here a personal comment by saying that GVT is maybe considered a trivial type of work because its results can be so rapidly shown, but it is nothing of the sort. Experimental work comes with a lot of challenges that need to be fixed fast and efficiently in order to be able to keep up with the schedule that an engineer must comply with.

For each wing set, over 160 points were measured, including leading edge points, relevant for in-plane mode measurements. The points were mapped and were then marked on the wings for easier and faster testing.

For the case of the flexible wings, the inboard part of the wing, were positioned differently, because due to the different structure properties of the wing, the points were placed on the spar and ribs instead of the same points as in the rigid case, the outer skin.

This happens because in the inboard part of the flexible wings the existing skin panels are not structural elements, just aerodynamic. Which means, if they were to be impacted, no relevant data would be collected, because even though they are connected to the structure, they are not truly a part of it.

For the testing purposes, only the top panels were removed in order to not change the proprieties of the wings with the missing weight related to it. The measured points are only placed in the structural parts: the spar and the ribs, where proper modal testing can be performed.

4.3. Conventional Rigid Wings Testing Results

In Figure 1 it can be seen the QT1 with the conventional wings installed and ready for shaker testing with the foam simulating the free free boundary condition.

Since this was the first time testing an aircraft, everything was slower at first, as can be imagined, and setted up the testing procedures for the rest of the testing phase.

Figure 1: QT1 Aircraft with Rigid Conventional Wings

Since all the testing procedures were already explained in previous chapter, it is stated here only the results obtained for for testing configurations: fixed cantilever and free free boundary conditions.

This set of wings didn't present any major challenge since the results, as espected from the what was seen in the FE models, were all linear.

For the fixed cantilever condition impact testing was performed, as for the free free conditions, shaker testing was the chosen technique.

For this set of wings, different boundary condition simulations were done, firstly the fixed cantilever was done, where the wing is mounted to a a rig that simulates the placing of the wings in the aircraft and that is afterwards bolted down to a table ready for ths type of tests.

For the free free condition, both bungees and foam conditions, as seen in Figure 1, were used.

4.4. Flexible Wings Testing Results

For the flexible set of wings, two cases were analysed: uninstrumented wings and instrumented wings. The purpose of this was to see how much it would affect the presence of all the cabling, sensors and actuators in the vibration modes of the wings.

The structural parts remain the same and the testing points are the same in both cases so that a complete correlation can be done for these two cases. The instrumented wing added strain sensors for a different mid-flight testing and static load tests for purposes beyond this thesis.

With all the wiring and sensors, the points remained in the same position but in some cases the points were no longer accessible, either from cables or sensors placed at the same spot or very near it, but in the end less of 5% of the locations were lost. Fortunately, this difference was not noticeable in the results.

It is relevant to say that the outboard part of the wing, from where the visible part of the spar ends to the wing tips (the major grey components), has the exact same dimensions and test points has the rigid wings.

The same testing procedure performed for the rigid wings involving shaker testing was done with this different wings set. Unfortunately, the results were far from optimal. The fact that this set of wings is less stiff because of its own structural configuration made it harder to acquire proper measurements.

A good shaker installation was very hard to find and countless hours were spent trying to improve it by having different support systems, different shaker mounts and even different shaker control signals.

In the end, the testing was finally performed resorting to impact testing, that was able to capture the lowest frequency modes with much better results than previously, thus guaranteeing the projects requirements.

The final results taken from the instrumented wings are presented in Figure 2.

Fixed Cantilever					Bungees				
Out of Plane Modes					Out of Plane Modes				
Mode #	Frequency [Hz]	Damping	Damping (%)	MPC	Mode #	Frequency [Hz]	Damping	Damping (%)	MPC
1	2,89	0,274	9,43	0,92	1	3,04	0,0414	1,36	0,94
2	17,8	0,377	2,11	1	2	17,9	0,0861	0,482	0,99
3	55,9	0,79	1,41	0,96	3	54,1	0,319	0,589	0,97
4	84,1	1,49	1,77	0,94	4	84,1	1,37	1,63	0,89
In Plane Modes					In Plane Modes				
Mode #	Frequency [Hz]	Damping	Damping (%)	MPC	Mode #	Frequency [Hz]	Damping	Damping (%)	MPC
1	12,9	0,0892	0,689	0,97	1	12,9	0,0892	0,689	0,97
2	15	0,234	1,56	0,67	2	15	0,234	1,56	0,67
3	22,7	0,374	1,65	0,89	3	22,7	0,262	1,15	0,71
Torsion Modes					Torsion Modes				
Mode #	Frequency [Hz]	Damping	Damping (%)	MPC	Mode #	Frequency [Hz]	Damping	Damping (%)	MPC
1	37,4	0,248	0,665	1	1	37,7	0,45	1,2	0,98

Figure 2: Final Results for the Instrumented Wings

5. FE Model Updating

The final step in this work is related to the updating of the Finite Element models, thus ending the cycle of the verification and validation process.

Even when a good model is created using finite elements, it only becomes reliable to use when backed up by some real information of the model. That makes the model creation a not easy thing to do.

For the case being analysed, the QT1, the important parts of the model to be updated are the wings, more specifically the wing's inboard and outboard parts. Consequently, these where the elements subjected to this sensitivity analysis to later perform the model updating. *As a note regarding FEMtools and the FE model, it will appear in the results numbered elements, where the element set number one will be correspondent to the inboard section of the wings and the element set number two will be the outboard part of the wings.*

From all the parameters that could have been chosen from the FEMtools software, the list of the ones that were picked is displayed at Table 2 as the responses picked, for the modal updating of the modal, the frequencies of the FE model were used.

Table 1: Parameters and Responses Used

Table 2: Parameter Selection (in color the selected ones for the 2nd Sensitivity Analysis)

Parameters Used	
JX	Mass Inertia about X
JY	Mass Inertia about Y
JZ	Mass Inertia about Z
GE	Structural Element Damping
E	**Young's Modulus**
RHO	**Mass Density**
AX	**Cross Section Area**
AY	Shear Stiffness Area for Plane XY
IX	**Torsional Stiffness**
IY	**Bending Moment of Inertia About Y**
IZ	**Bending Moment of Inertia About Z**
NSM	Non Structural Mass
MG	Lumped Mass

Regarding the previously mentioned Model Updating Settings the procedure, in order to have good results and a proper updating, it has to be well defined. To do that a two-step procedure was used: to follow the first parameter and then perform a continuation of the update with more stringent settings, as shown in 3.

Table 3: Updating Setting Steps

Updating Step	1^{st}	2^{nd}
ϵ_1	0,10	0,09
ϵ_2	0,06	0,05
Max $\dfrac{dP}{P}$ (%)	10.00	5.00
Correlation Criterion	CCTOTAL	CCTOTAL

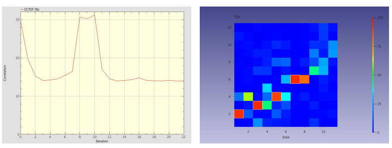
This two steps method was found to be the most effective one throughout the updating phase. Since the first step is already very strict, the second step only serves as a confirmation that the model is indeed converged.

5.1. Rigid Wings

For the rigid wings, the updating was processed smoothly and occurred without problems and the results can be seen in Figure 3 and in Tables 7 and 8.

It should be noted a very high discrepancy in the CCTOTAL plot in Figure 3(a) that is probably due to a poorly done updating step by FEMtools but, as can be seen, it was quickly fixed and it can be seen that the updating converged and reached the lowest possible value of CCTOTAL, implying the lowest difference between the FE model and the test data reached by the program.

In Table 7 it can be seen that the modal results in the end are really good, with MAC values in almost every case higher than 90 % and low frequency differences fin two of the modes, where the 4 th pair managed to be updated to perfection in relation to the frequency value, as the 1 st as well. **In terms of modal parameters it can be said that the updating was highly successful.**



(a) CCTOTAL Plot (b) MAC Plot

Figure 3: Results from the Rigid Wings Model Update

Regarding the updating parameters in Table 8 it can be seen that the in the majority of the cases there is a very large difference from the starting point to the updated results, with differences up to 40%.

5.2. Flexible Wings

For the case of the flexible wings model updating, the situation was not so easy. Considering that the GVT results were not optimal, the updating process was more difficult.

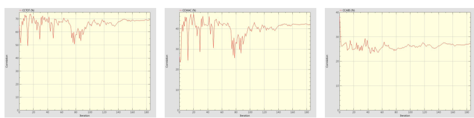
This problem was created because, since the wings are more flexible than normal, the results, that previously could be taken of just one of the accelerometers, now only showed good results for one of the wings. For that reason, where previously only one data set had to be used, now it had to be used two. This implied that Multi-Model Updating had to be done, where the model is updated taking into consideration multiple data sets.

The way FEMtools works obliges to create a unique project containing just one set of data for each wing. With that separation, computation problems were found, since it had its results divided into left wing, right wing and leading edge results. In the rigid case all the information could be set in just one project.

After being able to figure out how to manage the split data set, the updating process could be done. On a first try the results were by far non satisfactory. Using the same process used in the rigid wing was proved unsuccessful. The fact that the update was being done with separate projects wings caused the MAC values to be much lower that in reality. This was the main cause for the updating problems.

The update of the model had as a correlation coefficient the CCTOTAL, that according to **??** takes into consideration the MAC values from the mode shape pairs and since there is no mass updating or modal displacements take into consideration, the only relevant factors are CCMAC and CCABS. Knowing that the value of CCTOTAL should be as low as possible, values in the order of 70 % are not acceptable, as can be seen in 4(a).

The problem referred before related to the calculated MAC values by FEMtools in this situation can be seen perfectly in Figure 4(b) where there is a very non linear behaviour of the CCMAC values, nothing like the smooth convergence presented in the case of the rigid wings. The problem with the MAC goes beyond CCMAC and it is apparent that is affecting the CCABS factor, where the frequencies are almost converged at a fixed value, but the fluctuation accompanies the CCMAC value shifts.



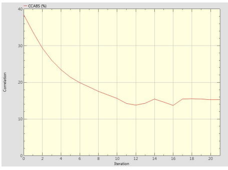
(a) CCTOTAL (b) CCMAC (c) CCABS

Figure 4: 1^{st} Results from the Flexible Wings Model Update

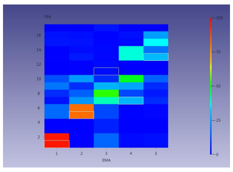
Since it is apparent that an update using the CCTOTAL coefficient won't lead to good results another approach was taken. Instead of CCTOTAL, it was chosen the CCABS coefficient, where, used with manual mode shape pairs, guarantees that the model is updated taking into consideration the proper model-experimental results combinations and still manages to update properly the model taking into consideration the modal frequencies.

With the approach change, the results are clear and the difference obvious, taking a look at Figure 5(a) it can be seen that the updating process is now much better. Reduced from 183 iterations to just 21 and with a very good convergence curve.

The values are now better as well: previously CCABS converged at the value of almost 28% and now it is at 15%. The improvement is very good.



(a) CCABS



(b) MAC Plot

Figure 5: Final Results from the Flexible Wings Model Update

In comparison to the results from the rigid wing, it can be seen in Table 10 that for this case the model was much closer to the reality than the rigid case. The most important parameters are the Young's modulus for the proper simulation of the new installed spars in the flexible wings and it can be seen that had a a very accurate value to begin with.

6. Conclusions

Fortunately, all the work done was performed without any major incidents. All the challenges faced were overtaken successfully and the solutions found were presented here in order to learn from these situations.

The major objectives of the work were completed successfully by having acquired good results for both wing configurations and by being able to update the FE models with those results.

The experimental modal testing yelded all the modal parameters for the two set of wings and used thecniques and methods used in order to be able to acquire them were described.

The update process of the FE models did present some challenges regarding the best correlation factors to be used, but they were overcome and they can now be used for the Embraer's bigger purpose of having them update the aeroeslactic models in order to have flight clearance of the QT1 UAV.

All the analysis done, following the guidelines given by Embraer, was focused on having the lower frequency modes very well documented and give them the priority on the analysis and on the model updating. Even with this constraint it was found that higher frequency modes were not so easily analysed and showed small non-linearities, thus the not inclusion of them in the FE model updating.

Taking a closer look at these modes it could be recognized that the methods and techniques used were not compliant with the proper detection and analysis of non linear modes. In order to have better results in those non linear modes, other methods sould be applied, if possible, as some of the ones presented in the state-of-the-art review made.

6.1. Future work

A deeper analysis of the non-linear modes present in the aircraft would be a very interesting topic to pursue, since it was found that the methods used were not ideal for non-linear mode analysis, only for linear modes.

Non linear modal analysis is a trending subject in the modal analysis field and should be pursued in order to make new findings of methods or techniques that enable the engineers to have better results, improving the whole process of Experimental Modal Analysis and FE model updating and structural analysis in general.

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Table 4: FE model Modal Frequencies for the Rigid and Flexible Wings Configuration

Rigid		Flexible	
Free Free	Fixed Cantilever	Free Free	Fixed Cantilever
7,39	6,69	3,06	2,83
21,70	35,22	7,86	11,10
37,07	58,83	12,10	15,70
53,06	101,18	16,30	15,90
65,20	176,05	16,60	50,00
103,00		23,80	54,00
		53,00	63,00
		57,40	64,00
		66,70	90,00
			91,00
			108,00

Table 5: Results for the Rigid Wing in Fixed Cantilever Boundary Condition (Impact Testing)

Mode #	**Frequency**	**Damping [Hz]**	**Damping (%)**	**MPC**
1	7,31	0,711	9,68	0,936
2	36,1	2,54	7,02	0,987
3	61,3	3,02	4,92	0,041
4	82,2	2,86	3,48	0,67
5	106	5,34	5,01	0,366
6	138	7,23	5,21	0,0565
7	179	5,75	3,2	0,65

Table 6: Results for the Rigid Wing in Free Free Boundary Condition (Shaker BC Foam)

Mode #	**Frequency [Hz]**	**Damping**	**Damping (%)**	**MPC**
1	7,48	0,0728	0,973	0,836
2	19,2	0,0193	0,1	0,913
3	26,7	0,338	1,26	0,995
4	30,8	0,272	0,883	0,919
5	33,5	0,373	1,11	0,99
6	39,3	0,788	2,01	0,318
7	46,1	0,237	0,515	0,964
8	50,2	0,643	1,28	0,964
9	67,3	1,26	1,88	0,96
10	89,9	1,54	1,71	0,663
11	126	5,64	4,46	0,367

Table 7: Results from Mode Shape Pairs in the Rigid Wings FE Model Update

Pair #	**FEA #**	**Hz**	**EMA #**	**Hz**	**Diff. (%)**	**MAC (%)**
1	2	7.4625	1	7.4752	-0.17	92.6
2	3	30.151	3	26.704	12.91	93.2
3	4	30.151	5	33.539	-10.10	88.5
4	6	46.057	7	46.058	-0.00	93.0

Table 8: Results from Parameter Changes in the Rigid Wings FE Model Update

Parameter #	**Type**	**Elem/Set**	**Old**	**Actual**	**Difference (%)**
1	E	1	7,00E+10	6,46E+10	-7,72
2	E	2	7,00E+10	5,66E+10	-19,11
3	RHO	1	1,28E+03	1,70E+03	32,86
4	RHO	2	6,40E+02	5,78E+02	-9,66
5	AX	1	1,43E-03	1,90E-03	32,93
6	AX	2	1,43E-03	1,29E-03	-9,56
7	IX	1	7,19E-08	8,01E-08	11,49
8	IY	1	1,93E-08	2,47E-08	28,06
9	IY	2	1,93E-08	1,60E-08	-17,03
10	IZ	1	1,50E-06	9,18E-07	-38,90
11	IZ	2	1,50E-06	1,48E-06	-1,79

Table 9: Mode Shape Pairs for the Flexible Wings FE model Update

Pair #	**FEA [Hz]**	**EMA [Hz]**	**Diff. (%)**	**MAC (%)**
1	2.7182	2.8903	-5.96	96.0
2	17.067	17.844	-4.35	82.3
3	47.114	54.503	-13.56	29.4
4	53.516	37.371	43.20	1.7
5	92.121	84.135	9.49	30.3

Table 10: Results from Parameter Changes in the Flexible Wings FE Model Update

Parameter #	**Type**	**Elem/Set**	**Old**	**Actual**	**Difference (%)**
1	E	1	6,89E+10	6,90E+10	0,14
2	E	2	7,00E+10	6,14E+10	-12,32
3	RHO	1	2,70E+03	2,74E+03	1,38
4	RHO	2	6,40E+02	6,97E+02	8,91
5	AX	1	1,71E-04	1,86E-04	8,73
6	IX	1	9,27E-09	6,63E-09	-28,49
7	IY	1	2,82E-09	3,20E-09	13,27
8	IZ	1	4,36E-08	5,27E-08	20,89