Parametric study of thin-layer boundary properties to emulate the dynamics of bolted joints of an aircraft component using finite element method and experimental modal analysis

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Abstract

In order to install new instrument into an aircraft especially rotorcraft type, vibration is an important issue to be concerned because vibration which is generated by rotor and other vibrated sources of rotorcraft might coincide with the new instrument installed. Therefore this event might let the instrument being damaged or crash of an aircraft. . This project aims to study the effect of changing bolted clamped condition of an aircraft instrument panel on dynamics response and natural frequency by using experimental modal analysis method and Finite Element Analysis. The bolted clamped conditions are adjusted by changing 1.bolt's diameter 2.bolt's spacing and 3.bolt's number. The result shows the effects of changing bolted clamped conditions on dynamics responses and natural frequencies. Finite element method is also used to create a thin-layer to emulate the dynamics responses and the 1st mode frequencies of all test cases in relation to experimental results. The thin-layer's property identified from finite element method can be used to emulate bolted clamped condition in further design and analysis without conducting experiment to achieve dynamics response and natural frequency of instrument. This process could cut the time and cost consumed.
***Keywords**:* rotorcraft, structural joints, experimental modal analysis, dynamics response, natural frequency

1. Introduction

Resonance is an event that frequency which is resulted from external force coincides with the natural frequency of the system. It is an important event that design engineer have to consider because resonance creates high amplitude vibration which leads to system damage. Furthermore in aircraft design procedure, resonance could also damage instruments such as meter, gauge, compass, radio transmitter and navigation system which are very sensitive to impact or vibration.

Nowadays, when aircraft manufacturers want to modify the performance by replacing old instrument with a new technology in the front panel before the pilot, it is not only the instrument that is replaced, but the instrument holding panel must be changed as well. The problem is that the new panel may have natural frequency which coincide with the aircraft's natural frequency. The manufacturers always have to make sure that the new instrument will not create resonant problem before that equipment will be in service.

From the information of Eurocopter South East Asia (ESEA), the solution for this problem is to re-design, test and adjust on the aircraft repeatedly until the natural frequency of the instrument does not coincide with the aircraft's system natural frequency. However, this solution consumes a lot of time and cost. So in 2011 ESEA has started a research about using Finite Element Analysis (FEA) to determine the natural frequency of the model and help aircraft customization process in order to reduce time and cost consumed. The feasibility of thin layer interfaces are also studied to model the dynamics behavior of aircraft component for further aircraft customization process.

Hence, this research will investigate furthermore in detail of the effect of changing bolted clamped condition of an aircraft instrument panel on dynamics response and natural frequency by using experimental modal analysis (EMA) and finite element method (FEM). The finite element model of the joint will include a special element namely, "thin-layer element" in order to emulate the dynamics response of actual joint. This would be useful and additional information not only for the aircraft customization process but also other application that bolted joint existing. The main advantage is to help all design process to cut the cost and time consumed, and also work efficiently by using provided information.

2. Basic theory

2.1 Thin-layer interface theory

The three most common mechanisms of joint mechanics are frictional slip at bolted or face-to-face compression joints, slapping at gaps, and reflection/transmission at locations of mismatch of mechanical impedance.

From the finite element code that we intend to develop dynamic models of joints, it is critical to determine only the simplest model possible which also captures the dominant physics of the joint. Even with fast modern computer, the micro-mechanisms of joint interfaces in not amenable to full system modeling. Interface elements have been developed to model the behavior of joints with different loading conditions. Two groups of interface elements are commonly used: zero-thickness and thin-layer interface element. In the zero-thickness interface elements, it is assumed that the interface has a zero thickness and a constitutive law which usually consisting of constant values for both the shear stiffness and the normal stiffness, is defined. The behavior of the thin-layer interface is assumed to be controlled by a narrow band or zone adjacent to the interface with different properties from those of the surrounding materials. The thin-layer element is treated as any other element of the finite element mesh and is assigned special constitutive relations.

As thin-layer elements are used for the simulation of the joints in the FEA. Experimentally determined contact stiffness and dissipation parameters are used as material properties of these elements. Thin layer elements are normal hexahedral elements in which length or width to thickness ratio can be up to 1000:1.

The stiffness (k) from the generic joint experimental must be transferred into the Finite Element model as a parameter of the Thin-layer elements. A schematic of an ability joint with a Thin-layer element is shown in Figure 1. The force (F) acting on both sides of the joint produces a shear stress (τ) in the Thin-layer element. The stress can be expressed as.

$$\tau = G\gamma \approx G\frac{u}{d} \qquad (1)$$

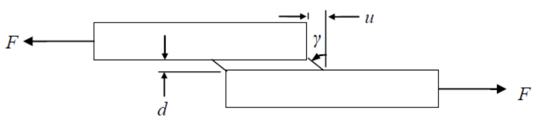

Fig. 1 Schematic joint

2.2. Modal Analysis theory

Mode are inherent properties of a structure, and are determined by the material properties (mass, damping, and stiffness), and boundary condition of the structure. Each mode is defined by a natural (modal or resonant) frequency, modal damping, and a mode shape (i.e. the so-called "modal parameter"). If either the material properties or the boundary conditions of a structure change then its mode will also change. For instance, if mass is added to a structure, it will vibrate differently. Multiple-degree-of-freedom (MDOF) systems are described by the following equation.

$$M\dot{x} + C\ddot{x} + Kx(t) = f(t) \qquad (2)$$

EMA is a method whereby experimentally achieving a structure in term of its natural characteristics which are the frequency, damping and mode shape. Let's consider a freely supported flat plate (Fig. 2).

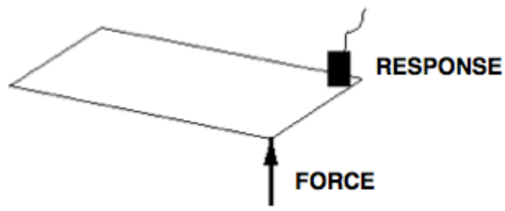

Fig. 2 Simple Plate Excitation/Response Model

Applying a sinusoidal force to one corner of the plate and consider a fixed frequency of oscillation of the constant force. We will change the rate of oscillation of the frequency but the peak force will always be the same value. We will also measure the response of the plate due to the excitation with an accelerometer attached to one corner of the plate. If we measure the response on the plate we will notice that the amplitude changes as we change the rate of oscillation of the input force. There will be increases as well as decreases in amplitude at different points as we sweep up in time. The response amplifies as we apply a force with a rate of oscillation that gets closer to natural frequency of the system and reaches a maximum when rate of oscillation is at resonant frequency of the system. The result achieving from accelerometer is time data and if we take the time data and transform it to the frequency domain using the Fast Fourier Transform then we can compute the frequency response function (FRF) which is the ratio of input spectrum to excitation spectrum.

$$H_{ij} = \sum_{r=1}^{n} \frac{\phi_{ir}\phi_{jr}}{mr(\omega_r^2 - \omega^2 + j2\zeta\omega\omega r)} \qquad (2)$$

Since ω : Frequency
ζ : Damping
$\{\phi\}$: Mode Shape

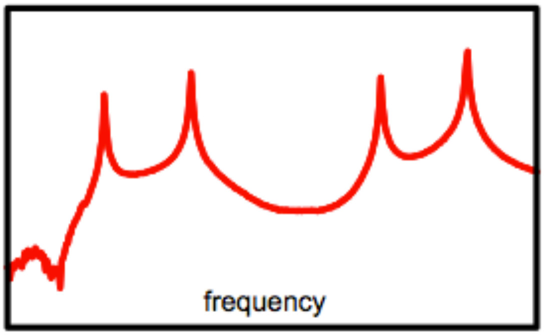

Fig. 3Simple Plate Frequency Response Function

There are peaks in this function which occur at the resonant frequencies of the system and these peak occur at frequency where the time response was observed to have maximum response corresponding to the rate of oscillation of the input excitation.

Let's place 45 evenly distributed accelerometer on the plate and measure the amplitude of the response of the plate with different excitation frequency. If we were dwell at each one of the frequency, we would see a deformation pattern that exists in the structure (Fig. 4). The figure shows the deformation patterns that will result when excitation coincides with one of the natural frequencies of the system. These deformation patterns are referred to as mode shapes of the structure.

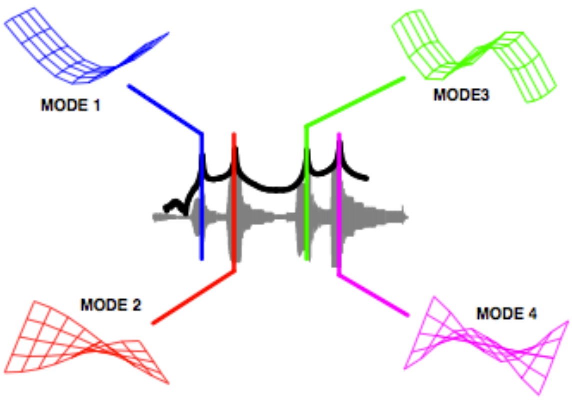

Fig. 4 Simple Plate Sine Dwell Response

3. Work Procedure

Firstly, we studied related literature, basic theory of vibration, thin-layer and basic modal analysis programing. We decided to separate this project into two parts which are experimental modal analysis and FEA. We did both parts alongside for saving the time and prompt solving problem if it occurs.

We started with FEA for studying effect of Thin-layer added and its properties in the model that Bianca Isabella Gursky[1] used to study with. The model is an aluminum plate which its dimension is similar to the front of the PS440 bracket of AS350 B2 aircraft. It also included thin-layer's thickness, density, Shear modulus and Young's modulus. All of this is the first procedure to make sure that Thin-layer theory can emulate the dynamics response of joints.

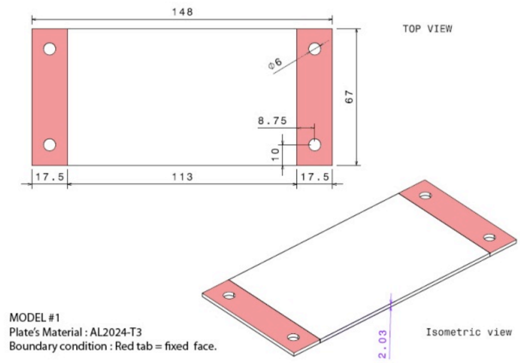

Fig. 5 Simple aluminum plate – PS440 dimension

Experimental part, the aluminum plate is used to fabricate the test structure and bolt is being used for studying joint conditions. The specimen set consists of a specimen plate and two supported plates (Figure 8) and clamped together by bolt with various joint conditions (Figure 6). The test set consists of several structures to transmit hydraulic pressure from hydraulic pressing machine to clamped specimen set on both sides of supported plate (Figure 7)

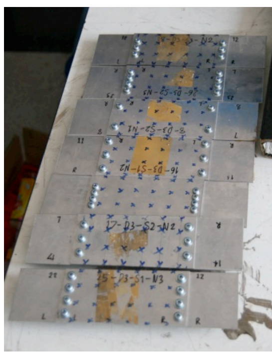

Fig. 6 Test plate

Fig. 7 Experimental setting

We started working on FEA in parametric study of each thin-layer's properties for choosing the most appropriate thin-layer's property by using its result to be a candidate parameter for matching procedure.

Once we got a trend line equation and experimental result, we used experimental result to be input data into trend line equation. So the output is parameter of thin-layer's properties. Then the parameter is used again to be simulated in FEA. The result and error which is output from FEA will be analyzed for choosing the most suitable thin-layer's property for matching.

After the matching procedure are finished, we did some validation with plain aluminum plate without joints, clamped on the both sides with hydraulic pressing. Its dimension is as same as specimen set (a specimen plate with attached to two supported plates).

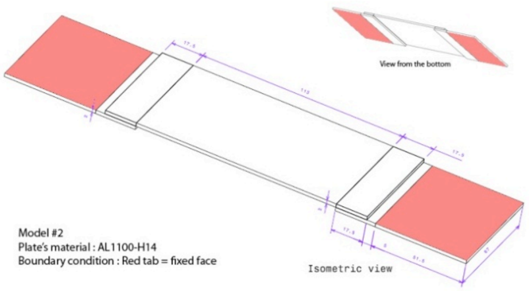

Fig. 8 Specimen set, consist of specimen plate and two supported plates

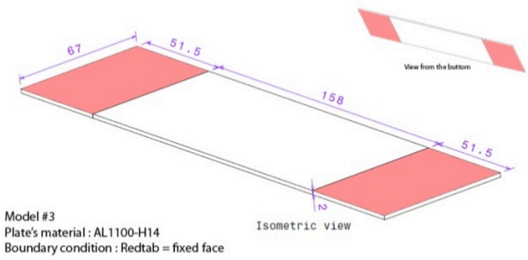

Fig. 9 Validation plate

4. Results and Discussion

4.1 Experimental results

The output of process is frequency response function (FRF), which generated from analyzing software by each case. The FRF composes of two types of data which are amplitude (y-axis) and frequency (x-axis).

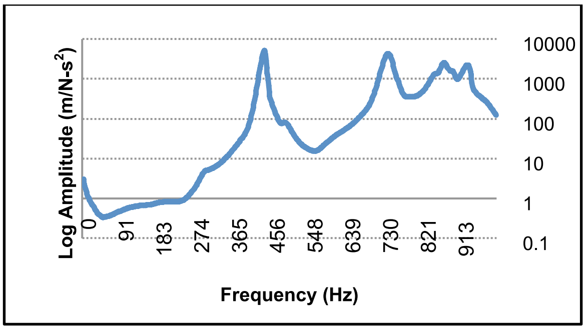

Fig. 10 Frequency response function of case 1

Since we have overall 18 test cases which covered 3 studied parameters (diameter, spacing and number of joint), all FRF from all cases were analyzed for achieving result of only the first mode frequency because the excitation in AS350 B2 aircraft is in range 0-100 Hz which can be covered by the first mode frequency of experimental results. Hence, only the first mode frequency is sufficient for investigating the vibrational damage within studied aircraft. The summarized results of first mode frequency (unit in Hz) are shown below.

Table. 1 Experimental result (First mode frequency) (unit in Hz)

	D1			D2		
	S1	**S2**	**S3**	**S1**	**S2**	**S3**
N1	440	465	460	395	410	390
N2	483	473	485	462	453	445
N3	487	462	460	442	440	433

Note

- D1: 4 mm diameter, D2: 5 mm diameter
- S1: Maximum spacing
- S2: Reduction by 20% from maximum
- S3: Reduction by 40% from maximum
- N1: 4 joints, N2: 6 joints and N3: 8 joints plate

The effects of changing clamped conditions are also investigated using the result of first mode frequency from all test cases (Table. 1). Fig. 11 showed the effect of changing diameter of bolt which the first mode frequency is decrease as increasing bolt's diameter.

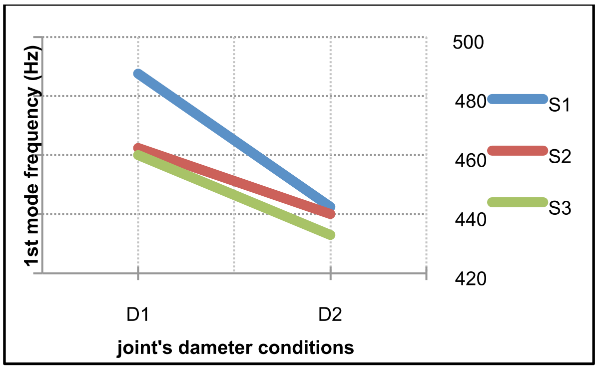

Fig. 11 First mode frequency of 8 joints plate (N3) with various joint's diameter conditions

4.2 Computational results

We have conducted computation using finite element method alongside with experiment. The specimen set model is being used as main computational model in order to generate thin-layer properties emulating the actual dynamics responses getting from experiment. Thin-layer thickness ratio (thickness: lateral length) 1:30 is chosen for studying and shear modulus is being a matching parameter because of the least error. Computational result of varying shear modulus vs. natural frequency (first mode) is shown in Figure. 12.

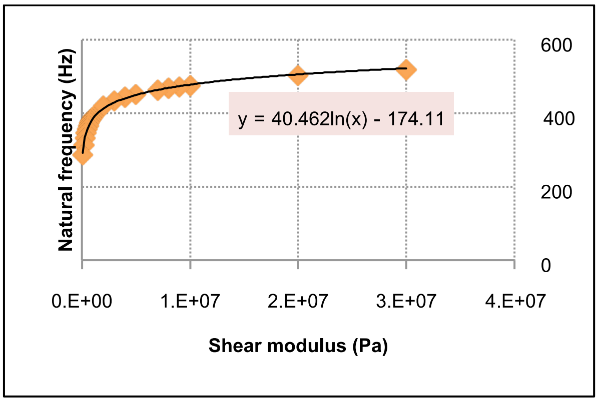

Fig.12 First mode frequency and it's trend line equation of Experimental testing model varying Thin-layer's Shear modulus fixed Thin-layer thickness ratio = 1:30

Mode shapes achieved from experiment and finite element method are also analyzed to see the difference result between both methods. Both methods could result precisely observed by mode shape deformation (Fig.13-14) that seem to have similar deformation.

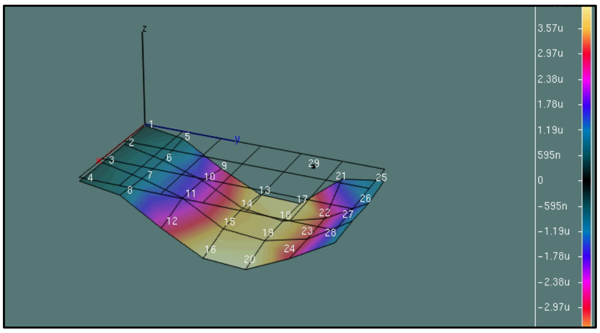

Fig.13 Mode shape deformation (first mode) from experiment

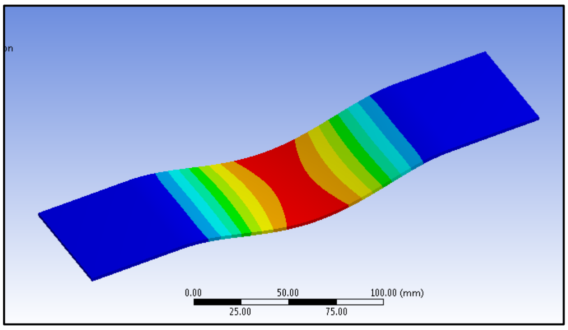

Fig.14 Mode shape deformation (first mode) from finite element method (*blue zone:clamped area*)

5. Conclusion

This research is originated from helicopter's application which aims to reduce the time and cost consumed of customization process. EMA, FEM and thin-layer theory are significantly involved in this research. 3 clamped conditions (spacing, number and diameter of joint) are chosen to be studied experimentally and computationally.

The 18 test cases are conducted experimentally and results are analyzed in 2 aspects which are effect of changing clamped condition on dynamics response specially 1st mode frequency and effect of changing clamped conditions on thin-layer properties that is added in finite element analysis to emulate the actual dynamics responses. The effects of changing clamped conditions are analyzed by using experimental result to differentiate the contrast the parameter in each test case.

The FEA is also conducted alongside with experiment. The meshing condition and sensitivity of thin-layer parameter are investigated and the appropriate meshing and thin-layer property are achieved for emulating the dynamics response of specimen that specially studied in 1st mode frequency of structure. Finally, the study got the thin-layer property parameter using for emulating dynamics response of all clamped conditions.

The identified thin-layer parameter can then be used to check the criteria of vibration to avoid resonance of new instrument that will be installed into aircraft. Hence, the utilization of this research is then provided by thin-layer property parameter and tendency of changing clamped condition to help the new customization process to cut the cost and time-consumed.

It should be noted here that the EMA results can be used to find the modal damping ratio[7]. Although it is not utilized as a part of our research.

Due to many factor involved during the experiment, the result quality might be affected by e.g. inaccurate test setup, specimen fabrication as well as impacting the specimen. Finally, those all inaccuracies will contribute to the error. Hence, The test setup, specimen fabrication and impacting the specimen should be significantly concerned during experiment because it will let to different in result quality and error.

7. References

[1] Bianca Isabella Gursky. (2011). *Applicationof Modal Analysis CAE toOptimize Aircraft Customization Design Process,* DiplomaThesis, F1027 D.

[2] Brian J. Schwarz and Mark H. Richardson. (1999). Experimental Modal Analysis, *CSI Reliability Week, October 1999*

[3] Hamid Ahmadian. (2003). Dynamic modeling of spot welds using thin-layer interface theory, paper presented in *10th international Congress on Sound and Vibration,* Stockholm, Sweden.

[4] H. Ahmadian and M. Ebrahimi. (2002). Identification of bolted-joint interface models, paper presented in *ISMA2002,* vol.8,September 2002, pp. 1741-1747

[5] MontreePirunkaset. (2008). Mechanical Vibration, Top Publishing, Bangkok.

[6] Patrick Guillaume. (2007). Control system robotic and automation Vol. V – Modal analysis, ELOSS.

[7] Peter Avitabile. (2011). Experimental Modal Analysis–A simple non-mathematical presentation.*Sound and Vibration,* vol. 35, January 2011, pp. 20-31.

[8] Sergey Bobrad, Andre Schmidt and Lothar Gaul. (2008). Joint damping prediction by thin-layer element, paper presented in 26th*Conference Exposition on Structural Dynamics 2008, Orlando, Florida.*

[9] William T. Thomson and Marie Dillon Dahleh. (1998). Theory of Vibration with Application, Prentice-Hall.