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AN INTEGRATED FINITE ELEMENT APPROACH TO MODEL BRAZING OF COPPER TUBES

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Abstract

Failure due to excessive vibration is one of the important concerns in designing mechanical structures and systems. This research focused on modal analysis of a multi-bent de-oxidized copper assembly tube being used in conventional air conditioning units. Currently, there is no specific method available to represent brazing connection of copper tube assembly. The main objective of this research was to identify an integrated approach to model brazing of copper tubes. Three joining methods were implemented, then finite element modal analysis was conducted to predict the dynamic properties of the assembly. Experimental modal analysis (EMA) was carried out to validate the corresponding Finite Element (FE) model. Comparisons between the natural frequencies of each joining method with EMA result revealed that surface to surface gluing method had the least percentage error difference of 5.2% when compared to the EMA result. As a conclusion, surface to surface gluing method which had more than 80% correlation with the experimental data was chosen as the best modelling method for brazed copper tube assembly.

Keywords: Finite element, Modal analysis, Model correlation, Tube assembly

1. Introduction

Most of the engineering systems have dynamic behaviour, through which loads vary with time. When dealing with dynamic loads, structural failure due to resonance is often a concern for industries especially in automotive and aerospace. For the past two decades, engineers and scientists have invested much effort to study the dynamic properties of structures by implementing modal analysis [1]. Defining the

Abbreviations

EMA	Experimental Modal Analysis
FE	Finite Element
ACM	Area Contact Method
DoF	Degree of Freedom
MAC	Model Assurance Criteria

dynamic properties of a structure plays a vital role in optimizing its dynamic behaviour and preventing the unwanted resonances. Unlike other well-established industries, modal analysis for air-conditioning mechanisms is not studied in details. In the history of air-conditioning industry, the study of vibration was started when Yusuhiro et al. [2] first made use of vibration analysis to develop a set of manuals for air-conditioning piping design. Later on, Ling et al. [3] came up with an idea to predict the vibration response of air-conditioning units through a digital simulation technique. Implementation of modal analysis in air-conditioning began after Chuan et al. [4] introduced a boundary condition to test pipelines of air-conditioning units during operation. Lim et al. [5] developed an integrated approach to FE model correlation on multi-bent deoxidized copper phosphorus tubes. Another research on modal analysis in air-conditioning is about using integrated software for finite element modal correlation of multi-bent deoxidized copper phosphorus tubes. To build up on the previous knowledge, current study has focused on more complex FE model correlation combining several tube assemblies. Figure 1 shows the actual design of the copper tube assembly that was studied in this project.

Fig. 1. Actual design of copper tube assembly.

In reality, copper tubes are assembled to each other through brazing to complete the refrigerant circuit. This assembly method is widely used in air-conditioning industries for copper-to-copper joining. The complexity of modal analysis on a copper tube increases as more individual copper tubes are connected to form an assembled structure. Numerical software is utilised to conduct modal analysis on the complex structure. Developing an accurate FE model of the assembly does not rely only on modal correlation, but also identifying an integrated joining method for FE model. In most of the commercial softwares, several built-in methods are available for users to define the connection between two structures. Out of those, Area Contact Method (ACM) and CWELD are widely utilized. These two methods are customized to model the actual welding conditions in automotive applications. In recent years, researchers also implemented them in analysis of structural dynamics [6, 7, 8]. In 2012, Wei et al. [9] utilized ANSYS to solve a finite element model of cable-stayed bridge and obtain the dynamic properties of the structure. Result from the analysis was used as a benchmark for various complex dynamic response analyses and long-term health monitoring. At the same time, Belver et al. [10] used FE modal analysis to identify the dynamic characteristics of a staircase and validate the result through experimental modal analysis. Salam et al. [11] implemented FE modal analysis to study the structure of a bridge and pinpoint the location of critical high stress zone. This result was validated with the experimental data obtained from waveform analysis.

There is no special custom method available to represent brazing connections of copper tube assembly. Hence, the main objective of this research was to identify an integrated approach to represent brazing connection of copper tubes. Joining methods were evaluated through the correlation of FE model of copper tube assembly and experimental data. The best joining method was then identified and selected to represent brazing of copper tube assembly. The length, thickness and diameter of the copper tube assembly being used in this research were 300 mm, 0.8 mm and 13 mm, respectively.

2. Methodology

2.1. FEM model development

The subject of this research was a multi-bent deoxidized copper tube assembly being used in an outdoor air-conditioning system. Finite element model of the assembly was created using Siemen's NX Nastran software. Fig. 2 shows the FE model of copper tube assembly created in NX Nastran software. A mid-surface model of the tube was created to simplify the FE model, and then meshed with CQUAD 4 (quadrilateral) elements of 1 mm size. Every node of CQUAD 4 element consisted of 6 Degrees of Freedom and a sum of 37731 CQUAD 4 elements were created over the entire FE model of the tube assembly. The abovementioned meshing configuration was justified by Lim et al. [5] in their paper on multi-bent deoxidized copper phosphorus tube. The material of the copper tube was selected as C10100 with a Young's modulus of 114 GPa.

Fig. 2. 3D CAD model of copper tube assembly.

2.2. Assembly method development

2.2.1. Surface to surface gluing

Surface to surface gluing is applied on the surfaces of two connecting objects to restrict the relative motion in all directions by creating a Surface-to-Surface Gluing simulation object. This is an effective way for joining two dissimilar mesh surfaces. The gluing region is consisting of elements located on the contact surfaces and was created using shell element BSURF [12]. Surface to surface gluing is one of the approaches being used in FE model of the copper tube assembly.

2.2.2. Rigid body element

Rigid Body Element (RBE) is a 1D element that enforces fixed constraints at the grid points where two components are connected. Motion of the grid point is governed by the DoF that is defined by the user. Mathematically, an RBE is created by multipoint constraint equations that each defines a dependent DoF as a linear function of independent DoFs. There are several types of rigid body elements fall under the same category which include RROD, RBAR, RBE2, and RBE3. From all these R-type elements, RBE2, and RBE3 are the most widely used elements in NX Nastran [12].

RBE2 is a rigid body link connected to an arbitrary number of grid points. Both dependent and independent nodes consist of three translational and rotational DoFs [13]. RBE3 is a rigid body link that expresses a constraint in which the displacement of a dependent node is the least square weighted average of the motions at other nodes. Although RBE2 and RBE3 are both R-type elements, but they are not the same. The major difference is that RBE2 adds artificial stiffness to the structure, while RBE3 does not [13]. In this research, both RBE2 and RBE3 were used to define the motion between two contact surfaces in copper tube assembly. Dependent and independent nodes of RBE2 and RBE3 were constrained with six DoFs because vibration of the structure is a combination of both translational and rotational motion.

2.3. Experimental modal analysis

In this research, experimental modal analysis was conducted to analyze the dynamic properties of copper tube assembly. Bruel and Kjaer instrumentation series, namely; miniature impact hammer type 8204, 0.65 milligram uniaxial accelerometer type 4517, FFT analyzer with 12 channel input module type 3053-B-120 and Bruel and Kjaer MTC Hammer were utilized. A total of 10 uniaxial accelerometers were mounted at several locations on the tube to gather the response of the structure due to vibration. Accelerometers were calibrated with Bruel and Kjaer calibration exciter type 4294 at 1 kHz before being attached to the copper tube assembly. The calibration error for the accelerometer is within the range of 3%. This experiment was conducted under free boundary condition, where structure was freely suspended in the space without any attachments to the ground. An elastic cord was used to provide free-free boundary condition for the structure. Measurements were conducted with a sampling frequency of 1024 Hz over the frequency span of 400

Hz. Linear averaging and transient weighting were applied in the analyses. Fig. 3 shows the experimental setup for the copper tube assembly.

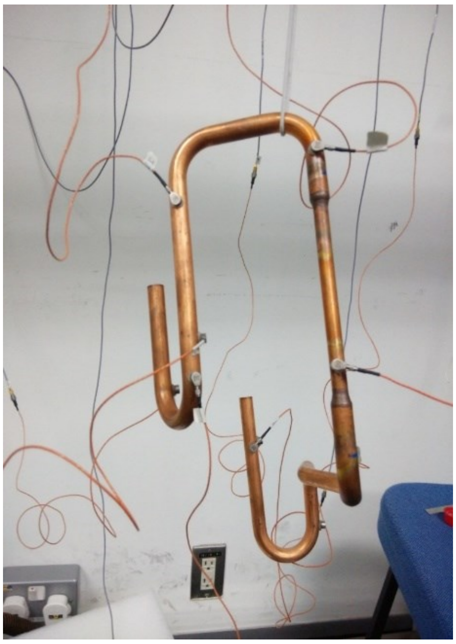


Fig. 3. Experimental setup for the copper tube assembly mounted in free-free condition.

2.4. Model correlation

Model Assurance Criteria (MAC) is a credible tool being used in industry for the comparison of mode shapes and natural frequencies obtained from the experiments to those from the FE model [14]. The degree of similarity between FE model and experiments is indicated by the correlation coefficient obtained from the MAC plot, varying between 0 and 1. A good correlation gives a correlation coefficient value of "1", whereas an uncorrelated mode shape is indicated by a correlation coefficient value of "0.1" [15]. A desired MAC plot has significantly high values for the diagonal terms (above 0.8) and significantly low values for the off-diagonal terms (below 0.1).

3. Results and Discussions

Modal validation is used to assess the accuracy of FE modal model with experimental results. This section starts with the study of modal behaviour of copper tubes before and after being assembled together. A good industrial practice is to validate the numerical result for each component before analysing the entire structure. For this purpose, the structure was divided into subsections "A" and "B" and the FE models were prepared using NX Nastran as shown in Fig. 4.

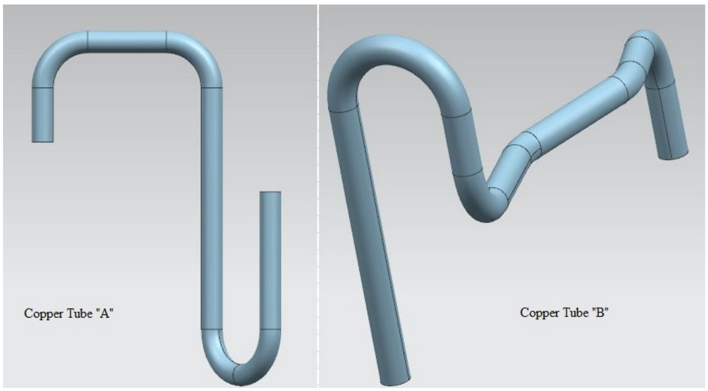


Fig. 4. FE models of the copper tubes “A” and “B” before the assembly.

3.1. Pre-processing of the tubes

Pre-processing of the tubes include meshing, selecting the material properties and defining the boundary conditions. The model of each component is created and meshed with CQUAD4 (quadrilateral) elements of 1 mm size. Each node of this element consists of 6 DOFs. The number of elements generated for copper tubes “A” and “B” are 14800 and 15862, respectively. The material selected for the tubes is C10100 copper with Young’s modulus of 114 GPa available in the material library.

3.2. Normal mode analysis of the tubes

Numerical modal analysis was conducted using Lanszoc method to extract the dynamic properties of the tubes. One mode was obtained for both tubes within the interested frequency span of 3 to 300 Hz, in compliance with ISO13355 for transportation of packages. Air-conditioning units are exposed to vibration at this frequency range while are being shipped from the factory to the end user. The natural frequencies for copper tubes “A” and “B” was 283 Hz and 199 Hz, respectively. These were in agreement with the results obtained from the experimental measurements that were 277 Hz for tube “A” and 192 Hz for tube “B”. The corresponding mode shape for both tubes is shown in Fig. 5.

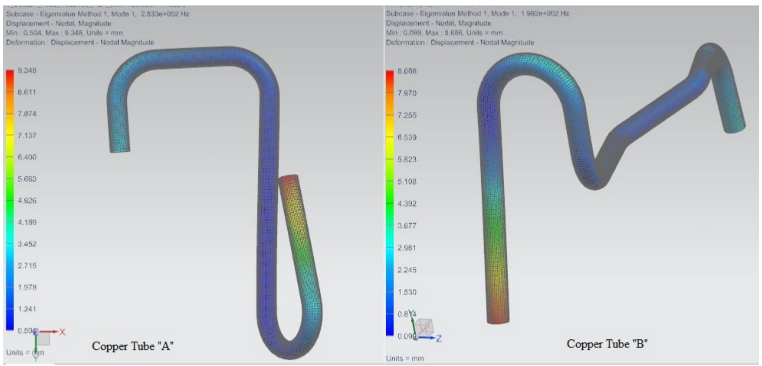


Fig. 5. The first mode shape for the copper tubes "A" and "B".

3.3 Numerical analysis of the assembly

The copper tube assembly was created and meshed with CQUAD4 element that produced a total number of 37731 elements. Copper C10100 was also selected as the material. Surface to surface gluing method was initially implemented to join the components together. Fig. 6 illustrates the surface to surface gluing method for the tube assembly.

Thereafter RBE2 and RBE3 joining methods were also examined to attach the FE model of copper tubes together. Finite element modal analysis was conducted for these three joining approaches. Dynamic properties of the copper tube assembly were obtained from the FE model and validated with experimental modal analysis. Table 1 shows the comparison of natural frequency for FE models of different joining approaches with the experimental modal analysis.

The numerical analysis of the assembly was conducted using NX Nastran solver 103. The natural frequency and mode shape of the copper tube assembly were extracted using Lanczos method. Within the frequency range of 3 Hz to 300 Hz, a total number of 7 natural frequencies and the corresponding mode shapes were predicted. Fig. 7 shows the mode shape of the copper tube assembly for mode 1, 4 and 6, these are bending modes at different natural frequencies. The natural frequency of each corresponding mode is shown in Table 1.

Based on the comparison between the natural frequencies of each joining method with EMA result, it was notable that surface to surface gluing method had the least percentage error with the EMA result, compared to that of RBE2 and RBE3 joining method. This result indicated that surface to surface joining method was capable of predicting the dynamic properties of copper tube assembly closer to the actual experimental values. The maximum and minimum percentage errors for surface to surface gluing method were 5.2% and 2.3%. These were slightly lower compared to the gluing method with the maximum and minimum percentage values of 5.27% and 2.32%. RBE3 joining method had the highest maximum and minimum percentage differences of 5.5% and 2.36%. In term of natural frequency, it was notable that surface to surface gluing method showed higher natural frequency, followed up by RBE2 and RBE3.

Natural frequency can be mathematically defined as the ratio of stiffness to mass for a system with negligible damping. From this theory, the effect of different joining methods on the natural frequency of copper tube assembly was identified. Copper tube was the only component contributing to the mass of the structure throughout the finite element analysis. The three joining methods did not contribute to any mass in the system. Hence, it was assumed that the mass of the system was constant throughout the analysis of copper tube assembly. The only factor which affected the natural frequency of the structure was stiffness of the structure. Surface to surface gluing method predicted the closest natural frequency to the experimental value and had the highest stiffness compare to the others. RBE2 exhibited higher natural frequency because it induced artificial stiffness. RBE3 was an interpolation element which did not add any stiffness to the structure. Unlike RBE2 and RBE3, surface to surface gluing method utilized glue element and assumed that the assembly part had welding like connection. As a result, the stiffness for this type of connection was much higher compared to RBE2 and RBE3.

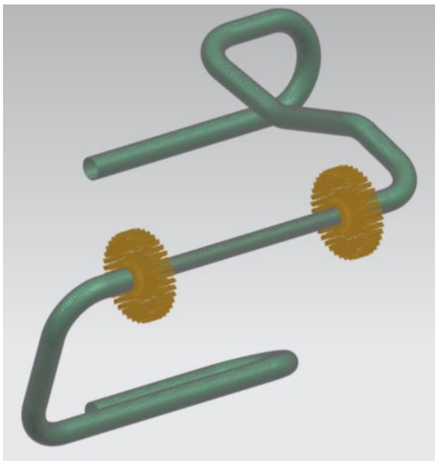
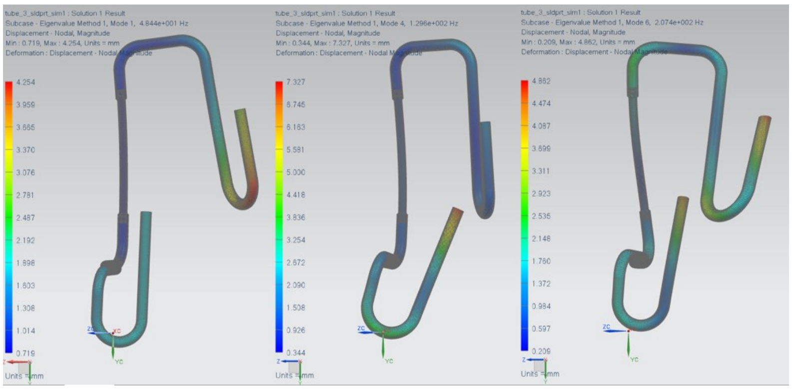


Fig. 6. Modeling approach for surface to surface gluing.



(a) (b) (c)

Fig. 7. Mode shape of copper tube assembly for mode 1 (a), 4 (b) and 6 (c).

Table 1. Natural frequency comparison for the three different joining methods.

Ref. Mode	**Natural frequency**				**% Error**		
	EMA	RBE2	RBE3	Gluing	RBE2	RBE3	Gluing
1	50.279	48.414	48.314	48.442	-3.708	-3.908	-3.653
2	65.863	62.391	62.243	62.435	-5.272	-5.497	-5.205
3	92.300	88.600	88.460	88.633	-4.008	-4.160	-3.973
4	133.679	129.529	129.410	129.556	-3.105	-3.193	-3.084
5	193.616	189.124	189.039	189.146	-2.320	-2.364	-2.308
6	214.184	207.282	207.039	207.357	-3.222	-3.336	-3.188
7	294.653	281.517	281.430	281.549	-4.458	-4.488	-4.447

Besides comparing the natural frequencies, comparison of mode shapes was also an important process in the validation process. Fig. 8 shows the MAC plot for the mode shape comparison between FE model and experiment. Symbol "R" represents the experimental mode shape and symbol "W" represents the one derived from the numerical model. No remarkable distinction was observed from the assessment of the MAC plot of each joining method. The deformation pattern in each mode shape was similar for all the joining methods. This phenomenon is common because the deformation pattern of any structure is a unique property of that structure that is not affected by the stiffness and mass. Stiffness and mass only affect the angle of deformation of the structure.

The purpose of modal validation is to ensure the accuracy of FE model compared to the experimental results. In addition to that, there are other important factors where CAE engineers are concerned about while running simulations. These factors include the time needed for computation and complexity of modelling of the joining methods. CAE engineers are often dealing with work pressure which enforces them to work efficiently within a short period of time. A comparison was made to identify the time needed for computation in numerical analysis of the assembly for different joining methods. Table 2 shows that Surface to surface gluing method consumed the least time for computing followed up by RBE2 and RBE3.

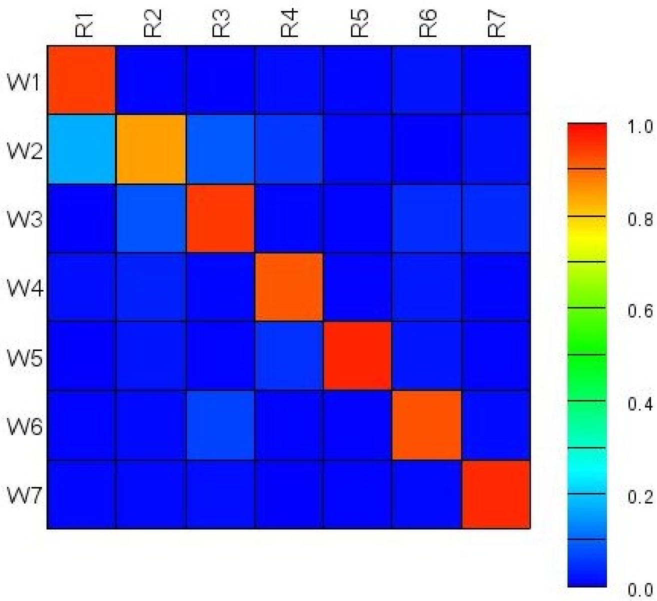


Fig. 8. MAC plot for surface to surface gluing, RBE2 and RBE3 joining methods.

Table 2. The required computation time for three different joining methods.

Joining method	Computational time
RBE2	70 min
RBE3	86 min
Gluing	39 min

In term of complexity, surface to surface gluing is the easiest modelling method because the assembly part can be defined easily by selecting the entire surfaces which are needed to be assembled together. However, RBE2 and RBE3 are much harder to model because the source and target node has to be defined manually for each element. A surface may consist of hundred nodes that all are to be defined separately. Hence, it takes more time and concentration to complete the structure for the whole assembly. Sometimes, it is required to make some necessary adjustment on the setting of the joining method. When such situations happen, RBE2 and RBE3 become very troublesome compared to surface to surface gluing method.

The model of copper tube assembly was validated with good correlation of greater than 80%. The predicted natural frequency was within the acceptable range. Different joining methods were implemented to identify the best approach representing the brazing of copper tube assembly. There were four important criteria in the assessment of a joining method. These were validity of the numerical model, computational time as well as complexity to model the joining method and if it was user friendly. Throughout the assessments, surface to surface gluing method was suggested to be considered as the integrated approach for modal analysis of copper tube assembly.

4. Conclusions

This study looked into dynamic properties of copper tube assembly using numerical and experimental approaches. The numerical modelling was dealing with different joining methods to connect surfaces for brazed copper tube assembly. Three joining methods were implemented, namely; surface to surface gluing and rigid body elements (RBE2 & RBE3) methods. Numerical modal analysis was conducted to predict the dynamic properties of the tube, which were then validated through experimental modal analysis. Correlation between FE models and experimental data showed that the natural frequency predicted by FE model was close to the experimental value. The percentage difference of natural frequency for both approaches was less than 10%. Good correlation results were also shown in the MAC plot, where the mode shapes from the numerical model correlates well with that of the experimental approach. Therefore the accuracy of FE model was assured through the validation process.

The next step was to determine the optimum joining method for brazing of copper tube assembly. Based on comparisons between the natural frequencies of each joining method with that of EMA result, it was notable that the surface to surface gluing method had the least percentage error, compared to RBE2 and RBE3. The maximum percentage error for surface to surface gluing method was determined to be 5.2% followed by RBE2 and RBE3. This result indicated that gluing element used by gluing method was much stiffer than RBE2 and RBE3. On the other hand, no remarkable distinction was observed from the comparison of mode shapes for different joining methods with EMA result. This phenomenon is common because the deformation patterns of a structure is unique and is not affected by the stiffness and mass of the structure. Besides comparing the accuracy, other factors such as computational time for each joining method, complexity of modelling and its user friendliness were also assessed. These results revealed that surface to surface gluing method is the best compared to the other methods. In conclusion, surface to surface gluing method, being easy to model and having a good correlation with experimental data was proposed as the modelling method for brazed copper tube assembly.

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