Study of various flexible joints as the thermal compensator elements in a typical light transport aircraft engine bleed system

Prashanth Banakara, H.T. Akshatha, M.L. Shankar and A. Rinku

Abstract

Engine bleed system helps in pressurisation and ventilation of aircraft cabin. Air tapped from the engine will be supplied to the bleed system, whose operating temperature and pressure will be of 340^0C and 140psi (differential) respectively. Due to the variation of temperature and pressure, the extension of pipes will produce high loads at the bends and supports, which should not exceed the limits specified by the engine manufacturer. Hence, it is necessary to choose a suitable thermal compensator to account for thermal expansion in the system and to reduce support reactions. The present work deals with study of various standard flexible joints like gimbals, bellows-braided and un-braided for engine bleed system of a typical light transport aircraft. For the simulation and analysis, commercially available finite element software like Altair Hypermesh and MSC Nastran were used. Initially, these flexible joint mechanisms were studied in isolation at element level and the results were compared with the guidelines of Expansion Joints Manufactures Association handbook. Once the study was found satisfactory, the compensators were introduced in the pipe system and analysis of entire assembly was carried out. During the study various parameters such as compensator location, their number, stiffness and optimal pipe routings were considered. Based on extensive study, braided bellows were found to be most effective thermal compensators for the present aircraft configuration. The braided bellow was designed and developed as per the analysis results and was successfully realised on the aircraft and found to function satisfactorily.

Keywords: Engine bleed system, bellows, gimbals, thermal compensator, flexible joints.

1. Introduction

Environmental Control System (ECS) or Air Management System is a generic term used in aircraft industry for system and equipment associated with cooling, heating, ventilation, humidity/contaminant control and pressurization within aircraft. The supply of air required for functioning of ECS in an aircraft is tapped from engines and conveyed through pipe system. This arrangement is termed as “Engine Bleed System (EBS)”. The hot air passing through the engine bleed system would be cooled and subsequently used for ECS of the aircraft. Due to high temperature of the air passing through the EBS, pipes would be subjected to expansion/contraction resulting in axial moment and swaying from their original configuration. These deformations in the system would results undesirable attachment loads, which can be avoided by introduction of suitable thermal compensator elements in the pipe system.

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Satoshi et al. [1], proposed a new kind of bellows called "Double Convolution bellows" (DCB) in which the convolutions are in two directions, the first convolutions are along longitudinal directions and the second convolutions are in the lateral direction. They have examined the behaviour of the bellows under various conditions like, repeated axial loading, internal pressurization and torsion loads. Faraji et al. [2], proposed a new method of manufacturing of metallic bellows and studied the effects of various design parameters using FEM and experimental tests. Abdulrahaman et al. [3], studied the relationship between maximum stress produced and life cycle of different shapes of bellow (U-shape, Ω-shape and disc-shape) by using simulation model written with the aid of MATLAB. Their investigation concludes that, out of three shapes of bellow section, U shaped bellows have smaller internal pressure-induced stress, longer fatigue life and is best suited for high internal pressure situations.

The present work deals with study of various standard flexible joints like gimbals, bellows-braided and un-braided for engine bleed system of a typical light transport aircraft (LTA). During the study various parameters such as compensator location, their number, stiffness and optimal pipe routings were considered. Based on the design studies and finite element analysis results customized braided bellows were developed and successfully implemented on the aircraft.

2. ECS of a Typical LTA

In LTA, the ECS air conditioning system (Fig. 1) operates using bleed air tapped from the engines by Engine Bleed System and supplies controlled conditioned air to the passenger and the crew compartments. Refrigeration is produced by a single bootstrap air cycle system.

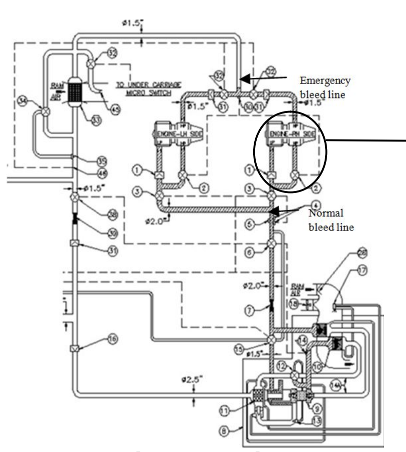

Figure 1: ECS bootstrap schematic

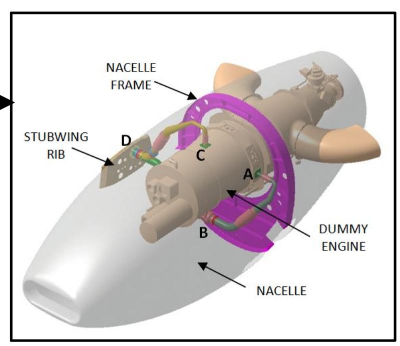

Figure 2: Engine bleed system in nacelle(details of nacelle are not shown here for clarity)

The engine bleed system is a combination of pipes of different size housed inside the engine casing called nacelle as shown in Fig. (2). The pipe inlets are attached to the engine tapping points 'A' and 'C' which are primarily used for tapping the hot air from the engine. The outlet end 'D' is attached to the main structural component called stubwing with an intermediate support at point 'B' on engine mount. Due to the predefined structural contour and fixed ECS configuration, the pipes are skewed excessively in all directions with unavoidable sharp bends.

During engine maximum operating condition, the EBS pipes would experience a maximum temperature of 340^0C and a differential pressure of 140psi. The main challenge involved in the EBS design is to limit the reaction at the engine bleed tapping attachment points to 1730kg-mm as specified by the engine manufacturer by considering the above mentioned design requirements.

3. Selection of Thermal Compensator Elements

The selection of thermal compensator elements were based on extensive design studies supported by Finite Element Analysis (FEA) and Expansions Joint Manufacturers Association (EJMA) [4] guidelines. Different design configurations were simulated using CAD software CATIA and finite element analysis were carried out using Altair Hypermesh and MSC Nastran. Initially to understand the system behaviour and the complexity of the problem, the FE analysis of the engine bleed system was carried out without considering thermal compensators. Model of the EBS without thermal compensator is shown in Fig. (3). Von-Mises stress plot is shown Fig. (4) and the attachment reaction are shown in Table1. It is clear from Table 1 that the maximum attachment reaction is 13102 kg-mm, which is much higher compared to the limiting value of 1730 Kg-mm. High attachment reactions and the high stress values near the tapping point indicates the need for thermal compensators in the EBS to counteract the pipe expansion and to minimise the support reactions.

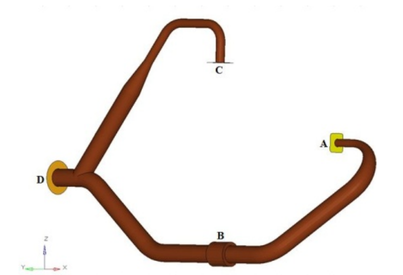

Figure 3: EBS without compensators

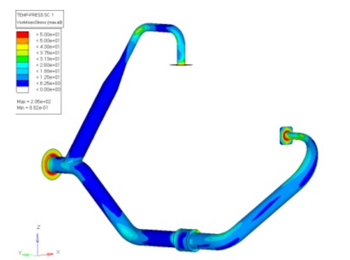
Figure 4: von-Mises stress plot without compensators

Table1: Tapping moments for the EBS without compensators

Tapping	Moment Mx (kg-mm)	Moment My (kg-mm)	Moment Mz (kg-mm)	Resultant moment (kg-mm)
A	9750	1210	-8668	13102
C	-8306	127	317	8313

Several different types of thermal compensator elements are used in aerospace industry. Each one is designed to operate under a specific set of design condition. The placement of the thermal compensator elements and their selection depends upon the designer's experience, understanding of its functionality and available anchoring points. Out of several the thermal compensators available in aerospace industry, un-braided bellow, gimbals and metallic braided bellows were explored in the present work. Design details of these compensators are shown in Fig. (5) and their application in the EBS is explained in subsequent paragraphs.

	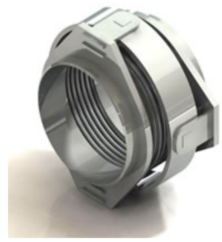	
Un-braid bellow	Gimbal	Metallic braided bellow

Figure 5 : Typical thermal compensator elements [5]

3.1 Engine bleed system configuration with un-braided bellow as a thermal compensator

Initially, usage of un-braided (open) bellow was explored in the EBS configuration. These kinds of bellows can be used for in-plane piping system between two rigid supports with allowance for axial moment. Typical un-braided bellows application is shown in Fig. (6). In the present EBS due to the predefined space constrain, skewed pipe system and fixed boundary conditions, these bellows were not suitable.

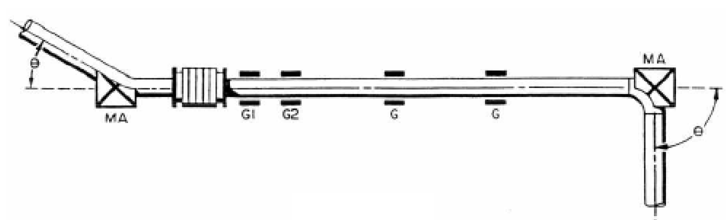

Figure 6: Application of un-braided Bellows [4]

3.2 Engine bleed system configuration with gimbal as a thermal compensator

Further, gimbals were explored in the EBS configuration as a thermal compensator. Gimbal expansion joint (Ball Joint) acts like a thermal compensator by allowing angular moment. It consists of two pairs of hinged connections to a floating ring (Fig. 5). When two or three gimbal joints are installed between two rigid anchoring points in a pipe system, they absorb–the axial and angular deflections through the combination of rotation in two principal directions. Gimbal joints were simulated with 2D shell elements and 1D bar elements. As the present EBS has complex pipe routings, the final design configuration has resulted in large number of gimbals as shown in Fig. (7). Maximum resultant moment at the tapping point for this configuration is 4660 kg-mm as shown in Table 2, which is much higher compared to the limiting value. And also results in stress values higher than the allowable (Fig. 8). Even though the attachment loads can be minimized to the acceptable limits by altering the locations of gimbals, further iterations/analysis were not carried out due to increased weight and cost aspects.

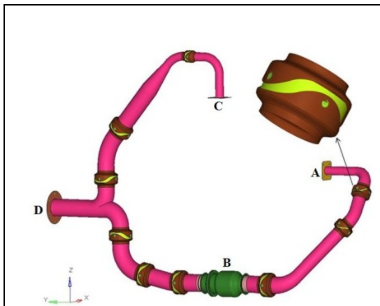

Figure 7: EBS with gimbals as thermal compensators

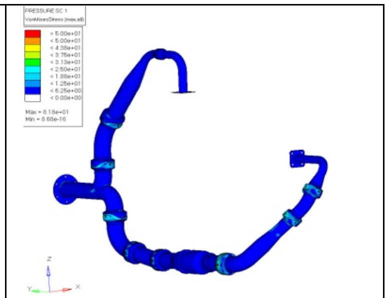

Figure 8: EBS von-Mises stress plot with gimbals as thermal compensators

Table 2: Tapping moments for the EBS with gimbal as thermal compensators

Tapping	Moment Mx (kg-mm)	Moment My (kg-mm)	Moment Mz (kg-mm)	Resultant moment (kg-mm)
A	254	14	4653	4660
C	-2	2	1	3

3.3 Engine bleed system configuration with standard braided bellow as a thermal compensator

As an alternative, commercially available off the shelf braided metallic bellows were investigated. Metallic braided bellows are made of convolutes with the steel wire wound over them (Fig. 5). They are effective in taking lateral as well as angular pipe deflections without requiring any additional guide support. These joints were simulated in FE using special 1D "CBUSH" element. The CBUSH elements have a unique feature of provision to specify translation and rotational stiffness in the required direction. This element helps in simulating the bellow mechanism near to the reality. EBS with standard braided bellow as thermal compensators is shown in Fig. (9). Properties of these standard braided bellows are shown in Table 3. Analysis of the system shows a good improvement/reduction in the support loads (Table 4) and stress was also found to be within allowable limit as shown in Fig. (10). Hence metallic braided bellow as thermal compensator was considered to be best suited for the present application. It is clear from Table 4 that maximum resultant moment at the tapping point for this configuration is 2113 kg-mm, which is near to the limiting value (1730 kg-mm) and requires change in the stiffness values of the bellows to meet the design requirements.

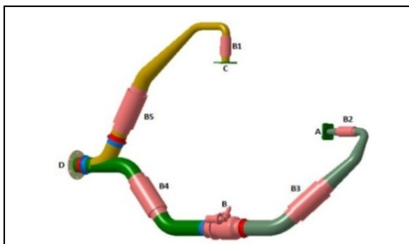

Figure 9: EBS with standard braided bellow as thermal compensators

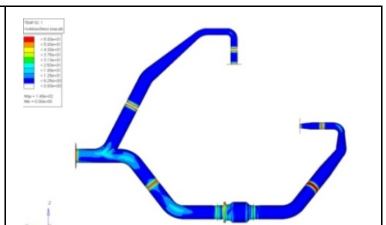

Figure 10: Von-Mises stress plot with standard braided bellow as thermal compensators

Table 3: Standard Braided Bellow properties

2-inch Bellow properties	1-inch Bellow properties
K2=15.43 kg/mm	K2=3.72 kg/mm
K3=15.43 kg/mm	K3=3.72 kg/mm
K5=0.03 kg-mm/deg	K5=0.013 kg-mm/deg
K6=0.03 kg-mm/deg	K6=0.013 kg-mm/deg
Where, K2 & K3 - Lateral stiffness K5 & K6 - Angular stiffness	

Table 4: Tapping moments for the EBS with standard braided bellow as thermal compensators

Tapping	Moment Mx (kg-mm)	Moment My (kg-mm)	Moment Mz (kg-mm)	Resultant moment (kg-mm)
A	1740	-51	-1197	2113
C	-610	32	21	611

3.4 Engine bleed system configuration with customized braided bellow as a thermal compensator

Based on the previous results, iterative analysis was carried out by varying the stiffness property the bellows. Initially FE analysis was carried out for each pipe segment in isolation with various stiffness values of the bellows satisfying EJMA guidelines and manufacturing feasibility. Optimum stiffness properties of the customized braided bellow are shown in Table 5. Stress and displacement contours for the final design are shown in Fig. (11) and Fig. (12) respectively. Final tapping moments for the EBS with customized braided bellow are shown in Table 6. The maximum resultant moment at the tapping point for this configuration is 1252 kg-mm, which is within the acceptable limiting value (1730 kg-mm) thus satisfying the installation requirements. The stress level in the system was also found to be within the material allowable limit. The maximum deflection was acceptable and found to cause no interference with adjacent structure.

Table 5: Customized Braided Bellow properties

2-inch Bellow properties	1-inch Bellow properties
K2=7.69 kg/mm	K2=5.14 kg/mm
K3=7.69 kg/mm	K3=5.14 kg/mm
K5=70 kg-mm/deg	K5=10 kg-mm/deg
K6=70 kg-mm/deg	K6=10 kg-mm/deg
where K2 & K3 - Lateral stiffness K5 & K6 - Angular stiffness	

Table 6: Tapping moments for the EBS with customized braided bellow as thermal compensators

Tapping	Moment Mx (kg-mm)	Moment My (kg-mm)	Moment Mz (kg-mm)	Resultant moment (kg-mm)
A	-1033	-26	707	1252
C	-22	417	22	418

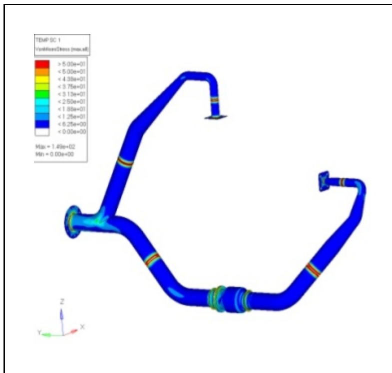

Figure 11:Von-Mises stress contour

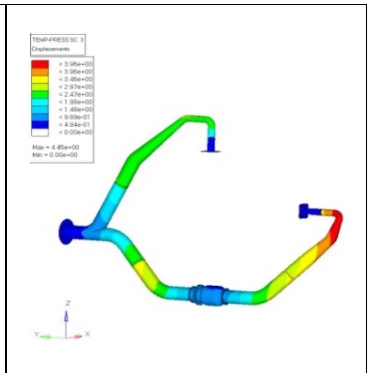

Figure 12: Displacement contour

3.5 Overall analysis of ECS

With the successful design and simulation of customized metallic bellows in EBS, similar methodology was adopted for the design of entire ECS system routing in LTA. The customized bellows developed for EBS were used at suitable locations and the detailed FE analysis of entire ECS was carried out. The detail analysis showed that the attachment reactions and the stress values are within the allowable limits thus ensuring the structural integrity. Fig. (13) shows overall ECS routing in rear fuselage with von-Mises stress contour.

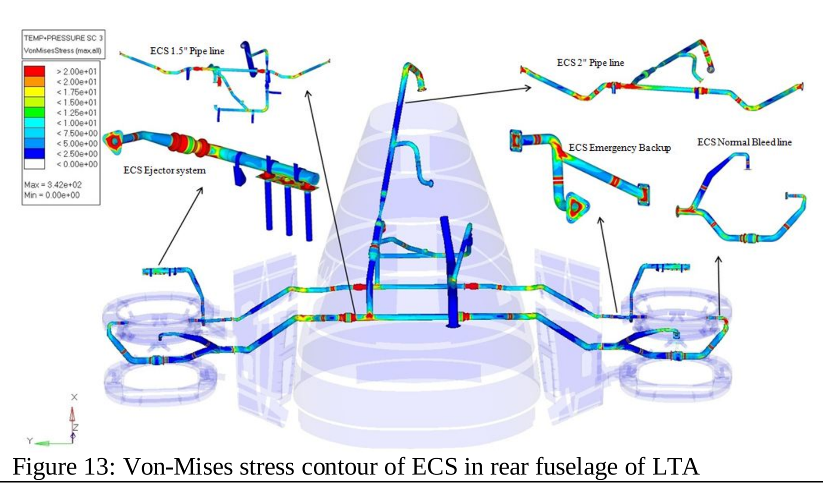

Figure 13: Von-Mises stress contour of ECS in rear fuselage of LTA

4. Results

The design studies of different flexible joints as thermal compensators for the EBS of LTA was carried out using CAE software CATIA, MSC Nastran and EJMA guidelines. Table 7 shows their comparison with respect to weight, tapping moments and their feasibility for the present application. Initial analysis without any compensators resulted in higher attachment reactions. The unbraided bellows were not suitable for the present application since it was difficult to either remove the pipe skewness or to provide additional supports. The simulation study of gimbals showed appreciable decrease in end attachment reactions with more number of gimbals as compared to braided bellows. This is uneconomical from weight and cost point of view. On the other hand, the metallic braided bellows customized to the present application were found to be suitable with the acceptable end moments. Iterative analysis with variation in bellows stiffness and their location in the pipe routing yielded an optimal design satisfying all design, installation, cost and weight requirements.

Table 7: Comparison of various thermal compensators

Compensator Type	Weight of EBS (kg)	Tapping moment* (kg-mm)	Design feasibility for present LTA
Nil	5.88	13102	Attachment reactions are high, infeasible design
Un-braided bellows	-	-	Requires additional guide supports and suitable for planar application, infeasible design
Gimbals	7.68	4660	Requires further design studies to reduce the end moments. Results in weight and cost penalty
Metallic braided bellows-customised	6.67	1252	Feasible design

*tapping moment limitation by engine manufacturer is 1730 kg-mm

5. Conclusion

This paper deals with the design simulation studies of different flexible joints as thermal compensators for the EBS and ECS of a typical LTA. Design and structural analysis studies were carried out using CAE software CATIA, MSC Nastran and EJMA guidelines. Various flexible joints like unbraided bellows, gimbals, and metallic braided bellows were considered for the study to check their application feasibility with the actual pipe routings on the aircraft. From the analysis, the un-braided bellows were found to be not suitable for the present EBS due to their single plane application limitation and anchoring requirements. Even though gimbals joints are superior to the metallic bellows, its implementation was not viable from cost and weight aspects for the present application. Whereas the customised metallic braided bellows were found to be best suited satisfying all the design requirements for the present application. Simulation of overall system analysis of the aircraft also showed that these customised metallic braided bellows were viable option from commercial, functional and weight point of view. Finally customised metallic braided bellows were successfully implemented on the aircraft and found to be functioning satisfactorily. The proposed simulation methodology can be adopted for any similar aircraft application in selection of suitable flexible joint depending on their design complexity, cost and other parameters.

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