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Hybrid Finite Element Analysis of Expansion Joints for Piping Systems in Aircraft Engine External Configurations and Nuclear Power Plants

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***Abstract*—**This paper presents a method to analyze the stiffness of the expansion joint with structural support using a hybrid method combining computational and analytical methods. Many expansion joints found in tubes and ducts of mechanical structures are designed to absorb thermal expansion mismatch between their structural members and deal with misalignments introduced from the assembly/manufacturing processes. One of the important design perspectives is the system's vibrational characteristics. We calculate the stiffness as a characterization parameter for structural joint systems using a combined Finite Element Analysis (FEA) and an analytical method. We apply the methods to two sample applications: external configurations of aircraft engines and nuclear power plant structures.

***Keywords*—**Expansion joint, expansion joint stiffness, Finite Element Analysis, FEA, nuclear power plants, aircraft engine external configurations

I. INTRODUCTION

EXPANSION joint is an assembly designed to hold together the members of tubular and pipe structures. Such joints are core elements found in many structures including nuclear power plants and aircraft engines where temperature-induced thermal expansion and tube/duct misalignment must be safely managed. In this regard, some researchers studied mechanical performances of certain type of expansion joints [1], [2]

It is important to find vibrational characteristics of such piping systems consisting of expansion joints for many applications such as aircraft engine external configurations [3], [4] or nuclear power plants [5], [6]. They are exposed to extreme vibrational conditions such as earthquakes and vibration disturbances due to unstable engine combustion. Expansion joints can change the vibration characteristics of the entire system due to such dynamic disturbances [7]. In this connection, we use the FEA to analyze the vibration characteristics of these structures and to assure their robustness under extreme vibrations in their design stages [8].

The system model is first divided into small pieces, elements in FEA. The more elements the model has, the more accurate the result is. However, the time and cost are increased proportionally to the number of elements. It is thus better to use as little elements as possible without affecting the results. For this, we simplify the components of such complex structures in order to minimize the number of required finite elements. If a system has expansion joints, it is not wise to generate elements for themselves but simplifying the model of its expansion joints is necessary and efficient step, from the perspective of time and cost.

In our FEA model, we simplify the expansion joint as weights and stiffnesses to find the stiffnesses by constructing a hybrid form of FEA and analytical methods. The proposed hybrid method is much faster and less expensive compared to FEA only approach.

Fig. 1 Example of expansion Joints [9], [10]

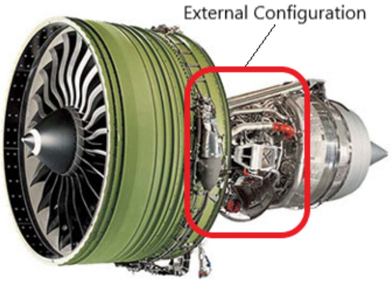

Fig. 2 GE90-115B engine with external configurations [13]

The expansion joint is composed of corrugated tubes and structural supports such as gimbals and rods as shown in Fig. 3.

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The corrugated tubes have multiple thin plies in it. The corrugated tubes and structural supports are connected in parallel like a set of springs. Thus, the stiffness of the expansion joints can be considered equivalently as an algebraic summation of corrugated tube stiffnesses and the stiffnesses of the structural supports.

The stiffness of the corrugated tube is obtained by an analytical method and the stiffnesses of structural support is assessed using the FEA respectively, then the stiffnesses calculated by the proposed method is compared with those obtained by the FEA-only model where the corrugated tube and structural support are all molded.

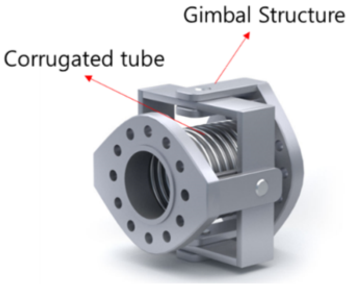

Fig. 3 Example of expansion joints with structural support [11]

II. STIFFNESS OF CORRUGATED TUBES

The analytical procedure and method used in this paper to calculate the stiffness of corrugated tubes is based on [12]. Total of four stiffnesses (spring rate) are calculated, that is, (1) the axial stiffness, (2) the bending stiffness, (3) the lateral stiffness, and (4) the torsional stiffness. The procedure of this method is described in detail in [12]. Only the resulting equations and stiffness results are shown in this paper.

TABLE I
NOMENCLATURE

Symbol	Description
C_t	Bellows wall-thinning correction factor
C_p	Ply interaction factor
d_i	Outside diameter of the convolution root of the bellows
d_m	Root-mean-square diameter of the bellows
E	Modulus of elasticity of the bellows material
G	Shear modulus of elasticity of the bellows material
h	Mean convolution height
L	Pitch of the bellows (axial length of a convolution)
N_c	Number of bellows convolutions
N_p	Number of bellows plys
t	Thickness of the bellows wall
L_a	Free axial length of the bellows

Axial stiffness (R_a) is calculated by:

$$R_a = \frac{1.49 C_t C_p N_p E d_i t^3}{N_c h^3}\ (for\ steel) \tag{1}$$

The bending stiffness (R_b), the lateral stiffness (R_c), and the torsional stiffness (R_t) can be expresses respectively as:

$$R_b = \frac{d_m^2 R_a}{458.4} \tag{2}$$

$$R_l = \frac{3 d_m^2 R_a}{2 L_a^2} \tag{3}$$

$$R_t = \frac{1.37\times10^{-2} G d_i t N_p}{(2h+0.57L)N_c} \tag{4}$$

Fig. 4 shows the CAD model of the expansion joint model of the gimbal structure used for stiffness calculation in this paper.

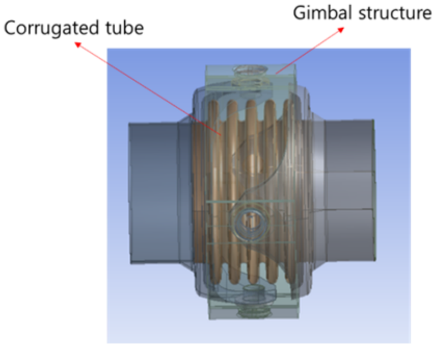

Fig. 4 Expansion Joints with structural support

The stiffnesses of the corrugated tube in Fig. 4 is assessed straightforwardly using (1)-(4). Table II shows the parameters and their values used to calculate the stiffnesses according to the properties shown in Table I.

TABLE II
PARAMETERS FOR THE CALCULATION OF THE CORRUGATED TUBE STIFFNESSES

Symbol	Unit	Value
C_t		1
C_p		1
d_i	*m*	0.066
d_m	*m*	0.0764
E	*Pa*	1.93E+11
G	*Pa*	7.50E+10
h	*m*	0.00975
L	*m*	0.008875
N_c	*EA*	5
N_p	*EA*	1
t	*m*	0.0005
L_a	*m*	0.0404

The calculated stiffness using (1)-(4) is in Table III.

TABLE III
CALCULATED STIFFNESS OF THE CORRUGATED TUBE

Symbol	Description	Value
R_a	*Axial stiffness (Pa)*	511,947
R_b	*Bending stiffness (Pa/rad)*	373
R_l	*Lateral stiffness (Pa)*	2,739,358
R_t	*Torsional stiffness (Pa/rad)*	10,207

III. STIFFNESSES OF THE STRUCTURAL SUPPORT

In this section, the stiffnesses of the support are assessed using the FEA. Fig. 5 shows the FEA mesh model to calculate the stiffnesses of the support.

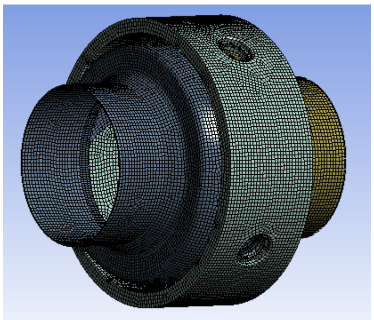

Fig. 5 The FEA model for the structural support of an expansion joint

The stiffness is defined as the resistance of a structure against the deflection by an applied force and thus it can be expressed as the applied force divided by deflection.

The boundary and loading conditions to find the stiffnesses of the gimbal structure is shown in Fig. 6. One side of the structure is fixed with six degrees of freedom and the other side is subject to applied force.

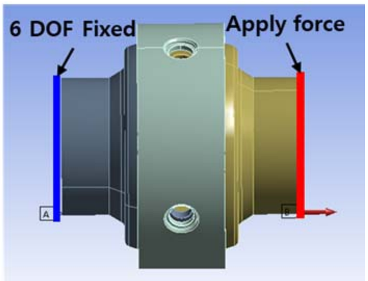

Fig. 6 Boundary conditions and applying loads

The stiffnesses are computed by dividing the applied force with deflections obtained from the FEA. By applying a force of unit magnitude, the stiffness can be simply calculated by the inverse of deflection (1/deflection).

Table IV denotes the stiffnesses of gimbal structure obtained by the FEA.

TABLE IV
THE STIFFNESSES OF GIMBAL STRUCTURE

Symbol	Description	Value
R_a	*Axial stiffness (Pa)*	34,913,763
R_b	*Bending stiffness (Pa/rad)*	0
R_l	*Lateral stiffness (Pa)*	13,236,968
R_t	*Torsional stiffness (Pa/rad)*	55,503

IV. STIFFNESSES OF THE EXPANSION JOINTS

Now, the stiffnesses of the expansion joint can be denoted by the algebraic summation of corrugated tube stiffnesses shown in Table III and those of gimbal structure stiffnesses given in Table IV. Table V shows the resulting stiffnesses of the expansion joints in the gimbal structure.

TABLE V
THE STIFFNESSES OF THE EXPANSION JOINT

Symbol	Description	Values
R_a	*Axial stiffness (Pa)*	35,425,710
R_b	*Bending stiffness (Pa/rad)*	373
R_l	*Lateral stiffness (Pa)*	15,976,326
R_t	*Torsional stiffness (Pa/rad)*	65,710

V. COMPARISON OF THE STIFFNESSES FROM THE PROPOSED METHOD AND THE STIFFNESS FROM THE FEA-ONLY MODEL

We are now comparing the results obtained by the proposed hybrid method with those from the FEA-only model.

TABLE VI
COMPARISON OF THE COMPUTED STIFFNESSES OF THE EXPANSION JOINT

Symbol	Stiffness computed from proposed method	Stiffness from FEA-only model
R_a	35,425,710	34,686,091
R_b	373	385
R_l	15,976,326	14,575,560
R_t	65,710	77,328

As shown in Table VI, stiffnesses obtained from the proposed hybrid method fall within tolerable ranges as compared to those calculated from FEA-only analysis.

VI. SUMMARY AND CONCLUSIONS

A simple method to find the stiffnesses of expansion joints in conjunction with corrugated tube and structural support was proposed in this paper. For this, the complex nature of the corrugated tube consisting of multiple thin plies demand time and cost to calculate its stiffnesses using a conventional FEA-only approach. The proposed hybrid technique is based on analytically calculating the stiffnesses of the corrugated tube and computing the stiffness of the support using the FEA instead of using FEA-only.

It shows that the stiffnesses obtained from the proposed hybrid method matches well with those obtained from the FEA-only model. Thus, we may conclude that the stiffness of expansion joint can be calculated more rapidly and cost-efficiently by the proposed hybrid method than the FEA-only approach.

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