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Integrating the flexibility of components in the assembly of aeronautics hydraulic systems

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Abstract: In this paper, we are focusing in the tolerancing of great dimension hydraulic systems which are overconstrained. For such systems, components fixings are linked to a rigid structure which more generally presents geometrical deviations. Moreover, pipe manufacturing process also creates some variations. The contribution of our approach is to determine by simulation the mechanical stresses between components, introduced by the actual geometry and the brackets position. In the paper, we first present the technological components characteristics, their geometrical manufacturing deviations and the joint constraints between components. Then we detail the proposed model which relies on a classical strength of material approach. In particular, this model uses tube flexibility in order to make-up for the manufacturing and positioning geometrical deviations. At final, this approach should lead to define the allowance amplitude of the different geometrical deviations.

Keywords: tube assembly, geometrical deviations, deformation, stress

1. INTRODUCTION

In aeronautics industry, installation systems are assembled at the end of aircraft's assembly sequence on brackets which are already positioned in a previous step of assembly sequence; these assemblies are achieved on a deviated geometry which may generate geometrical gaps between CAD model and actual geometry.

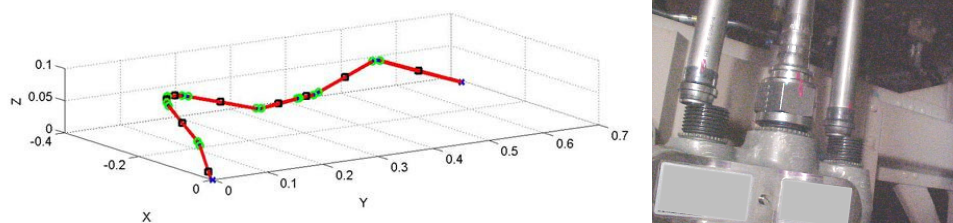


Figure 1; Nominal geometrical model and deviated actual geometry

To compensate these deviations, geometrical deformations must be applied to tubes but it appears internal stresses in joints which must be controlled.

A problem to solve is the geometrical deviations assessment of such mechanism. So we are interesting in tolerance analysis of pipes assembled on a non-rigid mechanical structure. To achieve this tolerances analysis, it requires knowing, on the one hand, the geometrical deviations of manufactured tubes in relation to CAD model and, on the other, the brackets position deviations in relation to CAD model. So, deviations knowledge also leads to carry out a geometrical behaviour simulation to define deviations influence on functional requirements.

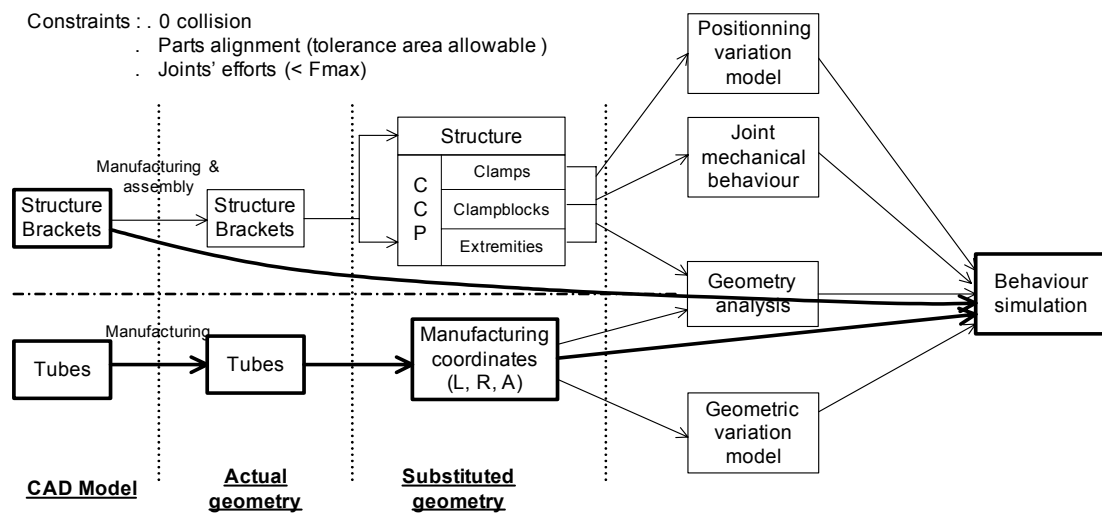


Figure 2; Tube tolerance analysis diagram

In this paper, a pipe assembly behaviour simulation which takes account the brackets position from CAD model is presented. Pipe measured geometry is considered as an input data for the model which enables to reach an estimate of forces and deformations applied on each joint. After a presentation of components assembly, an application of the behaviour model is exposed.

2. ASSEMBLY COMPONENTS

2.1. Bent tube

2.1.1. CAD model

A three-dimensional bent tube, formed with a numerical controlled rotary-draw bending machine, is considered as a sequence of straights and circular parts with a thickness (t) and an outside diameter (OD). All the circular parts are bent with the same tool called "bend die", so the following hypothesis, each circular element of one tube has got the same radius, is assumed.

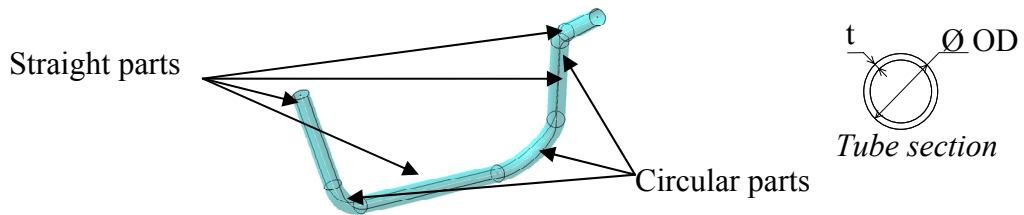


Figure 3; Bent tube (straight and circular elements)

Due to tube geometrical characteristics and above hypothesis, central axis of a bent tube is used to describe tube behaviour or geometry in different manufacturing steps (Design, process, measurement...). That's why, in design method it is considered as a discrete geometry composed of two types of characteristic points: extremities of the tube and virtual points which are called Intersection Point (IP). They represent the intersection of each straight element with the following one. To compare CAD model, actual and measurement geometry of pipes, a substituted geometry is defined according to NC bending process.

2.1.2. Substituted geometry

Two coordinate systems exist to define actual bent geometry and CAD model:

- Cartesian coordinate system for design (CAD model): X, Y, Z (extremities and intersection points, i.e. figure 4.a)
- Bending data for forming: length between bends L, rotation between bends R and bend angle A (i.e. figure 4.b)

It is easier to control physical points rather than virtual ones, as there are fewer uncertainties which may be carried out by approximation on virtual points' reconstruction method.

As there are three types of characteristics (L, R, A) to define a bent tube, we have chosen the following nominal geometry to illustrate these parameters:

	X Y Z Coordinates		
	X	Y	Z
Point 1	0	0	0
Point 2	0	151,854	0
Point 3	0	302,259	322,546
Point 4	151,573	71,326	254,735
Point 5	227,98	32,258	244,727

L R A Coordinates			
L mm	R deg	A deg	Bend radius
120	0	115	50
230	40	56	50
177	-63	150	50
73	0	0	

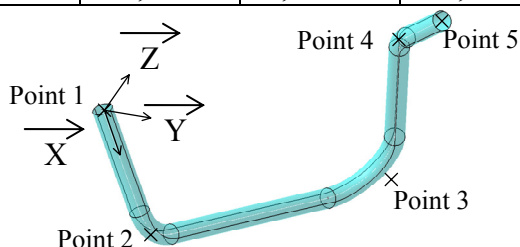


Figure 4.a; X, Y, Z coordinates (IP)

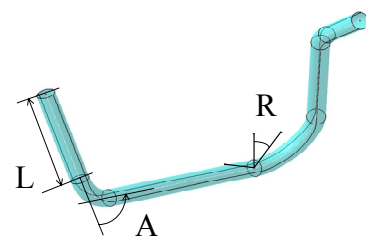


Figure 4.b; L, R, A coordinates

The substituted geometry: “L, R, A” is used to check that actual tube geometry corresponds to the nominal geometry. This generates a different discrete geometry composed of extremities of each straight element of one tube and where virtual points does not exist anymore, so it’s decreasing uncertainties due to different approximations.

2.1.3. Bending process

Tubes are formed with a numerical controlled rotary-draw bending machine, which generates some deviations on actual geometry. Due to its own geometry, two kinds of tubes haven’t same deviations for a same manufacturing process defect. The influence of manufacturing errors needs to be identified to achieve a piping geometrical deviation model for tolerance analysis. [Lou and Stelson 1, 2001] and [Zhan and al, 2006] had shown that bend angle error is the most influent source of deviations between the actual and designed geometry due to the elastic deformation (called springback phenomenon) after unloading. This deformation depends on many factors such as bend angle, tube geometry, tube material and bending machine.

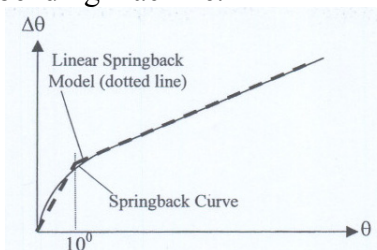


Figure 5; springback angle $\Delta\theta$ vs loaded bend angle θ ([Lou and Stelson 1, 2001])

Experimental tests have been achieved to validate Stelson’s model with the 20-120 method which consists in bending elements with angle of 20 and 120°.

When bending a 3-D tube with a die radius fixed, after unloading, the formed angle decreases because of material elasticity. So to respect a bent angle value, bending with a greater angle is needed, so the tube springs back to respect the theoretical bent angle.

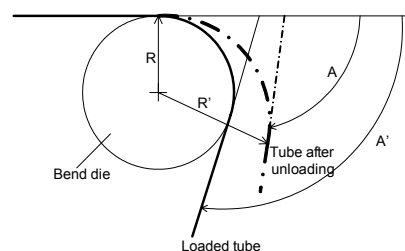


Figure 6; radial growth after springback ([Lou and Stelson 1, 2001])

But this creates a radial growth and so modifies the actual bent radius which has increased due to springback deformation. [Lou and Stelson 2, 2001] have developed a prediction springback model for NC bending machine compensation shown in Figure 5. The radial growth also generates errors on the distance between bends which must be corrected in the NC bending machine program. It illustrates the interdependency

between every manufacturing bending parameters to achieve a controlled geometry corresponding to CAD model.

To check the actual geometry, formed tube is measured ($\tilde{L}, \tilde{R}, \tilde{A}$) and needs to be compared with CAD model (L, R, A). The deviations between measured and nominal geometry depends on bending process capabilities and bending process adjustments. So with taking account these parameters in the simulation, it enables to establish a geometrical variation's model of tube integrating bending process capabilities ($\Delta L, \Delta R, \Delta A$) in order to find the influence of such capabilities on tube's geometry. Process capabilities are deduced from trial bends which are in progress.

Then we suppose we will know if the chosen process will be able to form CAD model tube with tolerance ($\delta L, \delta R, \delta A$) or if the bending process needs to be adjusted. These tubes are installed in an aircraft structure on different brackets' kinds which are called Controlled Check Point (CCP). As influence of manufacturing errors on tube assembly geometry has been expressed, positions' variation model of CCP needs to be defined to complete tolerance analysis.

2.2. Controlled Check Point

Controlled Check Points are used to constrain tube's position in an aircraft. There are lots of CCP technologies which are used with different kinds of tubes (with different material and geometrical properties). Three technological kinds of brackets to fix a tube are shown on figure 7a, figure 7b and figure 7c.



Figure 7.a; non rigid bracket



Figure 7.b; rigid bracket

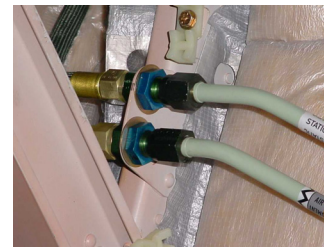


Figure 7.c; fixed extremity

A similar substituted geometry can be associated to each type of bracket: the centre's position and the main direction of the joint.

2.2.1. CCP's position error influence

As brackets are installed when all structure's parts have been assembled in the structure, actual assembly geometry doesn't correspond to nominal geometry thanks to manufacturing errors or structure's parts deformations for example. Then brackets are not well positioned which leads to different deviations between actual tube geometry and actual position brackets.

Like tube manufacturing errors, it seems important to integrate assembly capabilities (position and orientation variations) in our model to enrich it. With taking into account these parameters in the simulation, it enables to establish a positioning variation model

of brackets integrating assembly process capabilities ($\underline{\Delta u}$ for position and $\underline{\Delta w}$ for orientation) in order to find the influence of such capabilities on an assembly geometry. As this step is in progress and must be achieved by measurements in situ to obtain experimental results on assembly process capabilities, it's assumed that CCP positions correspond to theoretical ones.

2.2.2. Kinematical behaviour's joint's model

Each tube is fixed with several brackets, already positioned, on straight parts of tube, which creates a kinematical overconstrained mechanism. When a tube has all his degrees of freedom locked, deviations between brackets and actual tube geometry may appear due to, on the one hand, manufacturing process and, on the other one, brackets assembly process.

During the assembly path, tube extremities and rigid brackets allow two degrees of freedom: one rotation α_x and one translation u_x along bracket's axis. These CCP are considered to be rigid with no or very few deformation. Then we have chosen a fixed rigid body model with an associated kinematical torsor expressed in a local frame associated to the studied bracket:

$$\left\{ \begin{array}{cc} \alpha_x & u_x \\ 0 & 0 \\ 0 & 0 \end{array} \right\} \mathfrak{R}(O, \underline{x}, \underline{y}, \underline{z})$$

With O is the joint's centre and \underline{x} the bracket axis.

Non-rigid brackets allow two degrees of freedom: one rotation α_x and one translation u_x along bracket axis. But due to their flexibility, some displacements like 2 rotations α_y and α_z along other direction than bracket axis are available. Then we can consider such brackets as a sphere-cylinder joint with the associated torsor in the local bracket frame:

$$\left\{ \begin{array}{cc} \alpha_x & u_x \\ \alpha_y & 0 \\ \alpha_z & 0 \end{array} \right\} \mathfrak{R}(O, \underline{x}, \underline{y}, \underline{z})$$

As small displacements are introduced as a consequence of bracket stiffness, it's interesting to integrate in our model a brackets mechanical behaviour.

2.2.3. CCP's mechanical behaviour

To compensate gaps between actual and nominal tube geometry, some deformations must be exerted on the pipe geometry to constrained non rigid actual tube geometry to assembly with brackets. This forced assembly generates internal stresses in each joint where a force has been applied. If the bracket is non rigid, not only the tube, but the bracket is deformed too. So the joint has to find an equilibrium position after unloading the tube and then both bracket and tube positions have changed than before assembly. As the three kinds of brackets exposed have different stiffness, a same imposed deviation for each type of bracket doesn't ensure the same final joint position. A

mechanical trials' campaign to determine stiffness values of brackets and classify them by family has to be achieved.

2.3. Conclusion

If we take into account of all the above models, we expect respecting the following functional requirement: carrying out an assembly with minima efforts. A law of mechanical behaviour establishes the relationship between imposed deviations and exerted forces, and then the assembly force on each CCP is determined. So if some brackets have different stress limit they allow more or less relative deviations between them and tube to assemble.

3. BEHAVIOUR MODEL

3.1. The approach

This model relies on a classical strength of material approach. It needs material's characteristics, nominal and measured geometry, CCPs' positions and behaviour's law.

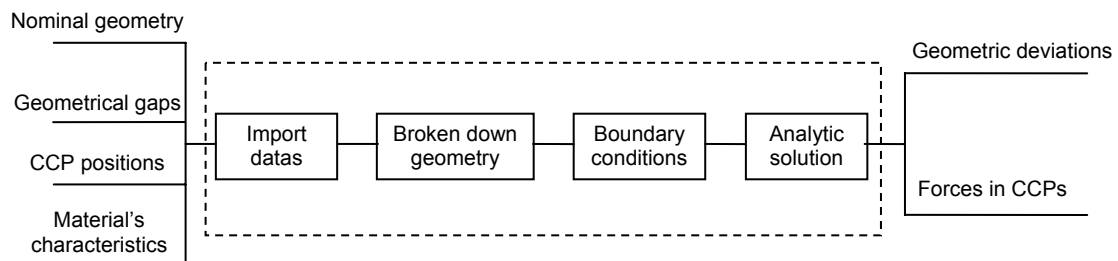


Figure 8; present behaviour simulation

The proposed model relies on the method exposed in [Cid, 2005]. It supposes we stay in linear deformation of components and we also consider small displacements. Then a linear static analysis to study forces and displacements can be used.

A tube is defined as an ordered sequence of straight and circular parts with following hypotheses:

- Outer diameter is well-known
- Bent radii are calculated with springback model
- Bent parts are supposed to be circular
- There are no geometrical discontinuities

The exposed hypotheses are assumed to simplify the exposed model and to work with only central axis [Mounaud, 2006].

3.2. Flexible behaviour model

The method is carried out to the four steps inside dotted lines on figure 8.

Firstly, importing data (nominal geometry, measured geometry, CCP positions and material and process characteristics) allows setting up the model.

In a second time, as a tube is considered as an alternative sequence of straight and circular elements, tube geometry is decomposed as such a sequence of elementary parts (straights or arcs of circle). In CAD model assembly, tube corresponds perfectly to brackets position. Each CCP is associated to one point on a straight element of the tube to define a discrete tube geometry by the following points: CCP and extremity (Ex_i and Ex_{i+1}) of each elementary part i . For each straight part i , a local frame ($Ex_i, \underline{X}_i, \underline{Y}_i, \underline{Z}_i$) is defined and CCP's position is expressed in this frame with local coordinates:

$$\{Ex_i, CCP_j = s_j \cdot X_i, 0 \leq s_j \leq L\}$$

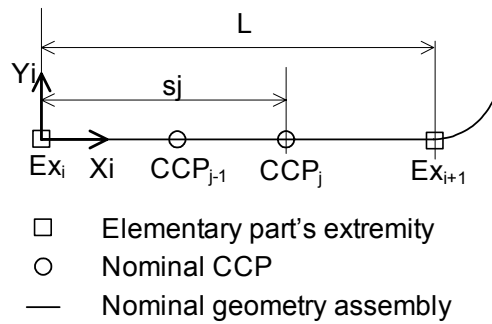


Figure 9; CCP's association to tube geometry

A discrete geometry represented by CCP and extremities of each elementary part is now available.

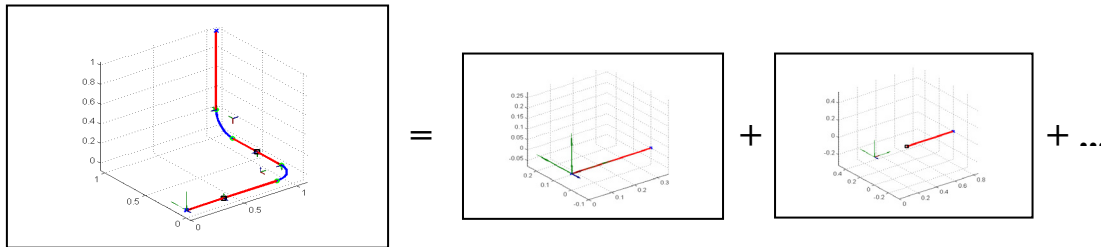


Figure 10; elementary parts sequence

The third step of the model concerns the tube's mechanical behaviour. Geometrical deviations between nominal (L, R, A) and measured geometry (or substituted geometry $\tilde{L}, \tilde{R}, \tilde{A}$) are calculated, they are considered as boundary conditions for the model we propose. Forces, which are linked to displacements by stiffness matrix, can indeed be exerted to impose deviations to the measured geometry to constraint it to assembly with the theoretical brackets positions.

Each element (straight or circular) of a tube is considered in equilibrium between two mechanical efforts at its own extremities: $\left\{ \begin{matrix} R_A \\ M_A \end{matrix} \right\}_A$ and $\left\{ \begin{matrix} R_B \\ M_B \end{matrix} \right\}_B$.



Figure 11.a; Straight element

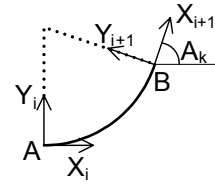


Figure 11.b; Circular element

Then we have two equilibrium relationships:

- $\underline{R}_A + \underline{R}_B = \underline{0}$
- $\underline{M}_A + \underline{M}_B + \underline{PA} \times \underline{R}_A + \underline{PB} \times \underline{R}_B = \underline{0}$ valid for every point "P" on the studied part

It's supposed we stay in linear, elastic and isotropic deformation; moreover small displacements, immaterial curving and homogeneous mechanical behaviour are the hypothesis made to use Bresse equations to link mechanical deviations to efforts on tube:

- $\underline{w}_A = \underline{w}_B + \int_A^B \left(\frac{M_{X_i}}{GJ} \underline{X_i} + \frac{1}{EI} (M_{Y_i} \underline{Y_i} + M_{Z_i} \underline{Z_i}) \right) ds$ for section's orientation
- $\underline{u}_A = \underline{u}_B + \underline{AB} \times \underline{w}_B + \int_A^B \frac{R_{A X_i}}{GJ} \underline{X_i} ds + \int_A^B \left(\frac{M_{X_i}}{GJ} \underline{X_i} + \frac{1}{EI} (M_{Y_i} \underline{Y_i} + M_{Z_i} \underline{Z_i}) \right) \times \underline{PB} ds$ for translation on every point "P" on the studied part.

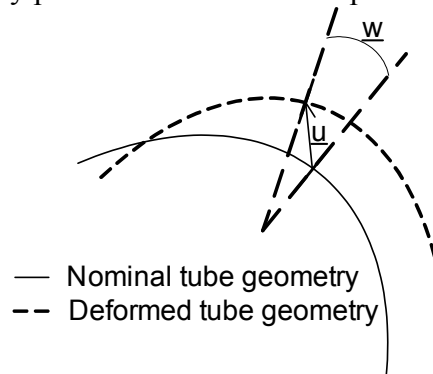


Figure 12 ; local motion parameters

The last step of model is the reconstruction of the tube. Deviations to compensate are considered as boundary conditions (imposed displacements). Elementary parts are linked together with rigid joints.

4. ACKNOWLEDGEMENTS

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5. CONCLUSION

Taking account the flexibility of components in an aeronautic assembly contributes to anticipate geometrical tube deviations to verify that deformed geometry belongs to the tolerance area. Objective of this paper is to present a behaviour model of a piping assembly which integrates manufacturing and assembly process errors, compliance properties of assembled parts. So, nominal geometry, geometrical gaps, material properties and CCP position are input data for the exposed model which allows determining geometrical deviations and efforts in the studied points. This model needs to be improved by working on the impact of tube's mechanical deviations on tolerance zone which is achieved by validation of presented models.

An original application of the complete model may be defined in control process using an effort criterion for acceptance. Rather than defining geometrical deviations available to make an assembly, it's possible to consider functional requirements as a limited effort for the different joints of the considered assembly. Joints are indeed associated to the part to assemble and we are able to know if local assembly effort respects the imposed limit.

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