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Factors Determining the Pipelines Installation Features during the Liquid Rocket Engine Assembly

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Abstract. A liquid rocket engine contains a vast number of pipelines. The present article describes some of the features with respect to the pipelines fabrication, introduces the main factors influencing the mismatches during the engine assembly, proposes an approach to the pipelines fabrication based on the application of the advanced design, calculation, fabrication and inspection methods based on the 3D geometrical model of an object. The existing technology of the assembly provides for the manufacture of the engine layout, the reference design of the templates. Manufactured pipeline in accordance with the standard for each specific instance of the engine requires adjustment. The exclusion of modifications and adjustments during assembly requires the use of modern methods of design, production and control based on the use of the model-oriented approach. Including calculation mathematical modeling of all processes occurring during the manufacture and assembly of pipelines.

1. Introduction

The liquid rocket engine consists of a large number of high-load units. The units are connected by means of the pipelines (Figure 1) operating under high pressure, temperature and vibration loads. It is required to ensure the maximum strength and tightness of all connections at the minimum weight and installation loads in order to provide the liquid rocket engine reliable operation.

Figure 1. Layout of the liquid rocket engine general assembly components
The majority of pipelines in the modern engines are installed “in-situ” in the course of the assembly. The existing assembly method provides for the engine mockup making, pipelines standardization based on the mockup and making of patterns [1, 2]. Since the engine mockup contains units having unique dimensions that differ from the nominal ones, the reference pipelines are fabricated for these particular unique dimensions [3]. So the pipeline fabricated in accordance with the reference standard requires adjustment for each particular engine. In addition, the development of rocket engineering requires a constant improvement of strength characteristics of the materials applied that creates additional difficulties in the pipelines fabrication.

2. Features the pipelines fabrication

The pipelines fabrication method depends on their structural design [4]. The following may be related to the main features of the liquid rocket engine pipelines design (Figure 2).

- spatial configuration;
- fabrication tolerances for the engine structural elements;
- application of high-strength steels and nickel alloys;
- difference of geometrical dimensions for each particular engine.

![Figure 2. Examples of small and mid-diameter pipelines of the liquid rocket engine](image)

The following issues shall be solved in order to provide for the assembly without prior adjustment at multi-knee spatial bending of pipes:

- determination of the extreme curvature of bending when no defects occur;
- determination of the actual coordinates of pipelines junction points for each particular engine;
- formation of the pipeline 3D design model considering the actual dimensions;
- development of a control program for a pipe-bending machine with numerical program control for each particular pipeline of each particular engine;
- fabrication of pipelines using pipe-bending machines with numerical program control.

Thus, the exclusion of modifications and adjustments during assembly requires application of state-of-the-art design, fabrication and inspection methods based on the use of model-centric technologies (technologies based on the use of geometrical 3D models).

Such an approach corresponds to the current engineering development trends, i.e. moving away from traditional approaches and methods based on the assembly accompanied by numerous metalwork operations: adjustments and modifications. Replacement of such operations with a "virtual"
adjustment - the development of the geometrical 3D model of the particular pipeline for the particular engine.
At the same time, it shall be noted that the above organizational and technical measures may solve the issue of pipelines assembly with no modification only upon consideration of a sufficiently wide range of design and process factors. The basic of the same are as follows:
- pipelines junctions point location tolerances;
- pipeline configuration;
- pipeline minimum bend radii depending on its material and diameter;
- presence and length of pipeline linear portions;
- accuracy of spatial coordinates determination;
- actual mechanical properties of the pipeline material;
- springback of the pipeline material depending on its dimensions during fabrication;
- pipeline bending method;
- residual stresses acting in the structure;
- pipeline material relaxation.

3. The value of mismatches in the course of the pipelines installation
The value of mismatches in the course of the pipelines installation may be significant, it determines the spatial position of the mating surfaces and is defined as the vector sum of a large number of values. In general, the value of mismatches in the course of the pipelines installation may be determined as follows:

\[
\Delta \bar{A} = \delta \bar{A}_t + \delta \bar{A}_a + \delta \bar{A}_p + \delta \bar{A}_r + \delta \bar{A}_s + \delta \bar{A}_i + \delta \bar{A}_j,
\]

\[
\delta \bar{A}_t = \delta \bar{A}_{t_h} + \delta \bar{A}_{t_o} + \delta \bar{A}_{t_i} - \text{deviation from the true position due to the fabrication tolerances;}
\]

\[
\delta \bar{A}_a = \int (l_x - l_{n_x}) \, dx - x \text{ offset;}
\]

\[
\delta \bar{A}_p = \int (l_y - l_{n_y}) \, dy - y \text{ offset;}
\]

\[
\delta \bar{A}_r = \int (l_z - l_{n_z}) \, dz - z \text{ offset;}
\]

\[
l_x, l_y, l_z – \text{actual coordinates along axes } x, y, z \text{ correspondingly;}
\]

\[
l_{n_x}, l_{n_y}, l_{n_z} – \text{nominal values of coordinates along axes } x, y, z \text{ correspondingly;}
\]

\[
\delta \bar{A}_t - \text{deviations due to the inspection accuracy when determining the spatial coordinates while inspecting the actual dimensions of junction points;}
\]

\[
\delta \bar{A}_a - \text{deviations due to the difference between the actual mechanical properties and nominal values;}
\]

\[
\delta \bar{A}_p - \text{deviations due to the springback of the spatial pipeline in the course of its fabrication;}
\]

\[
\delta \bar{A}_r - \text{deviations due to the pipeline material relaxation;}
\]

\[
\delta \bar{A}_s - \text{deviations due to the pipeline internal stresses;}
\]

\[
\delta \bar{A}_i - \text{deviations due to the temperature deformations resulted from the temperature difference in
the course of the pipeline fabrication and engine assembly:

$$\delta A_j$$ - deviations due to the cross-section deformation in the course of the pipelines fabrication.

In this case, the largest contribution to the mismatches is made by the springback that depends on such factors during bending as the pipeline mechanical properties and wall thickness, bending radius, pipeline shape, bending methods, etc. The uniformity of the pipeline fabrication material mechanical properties significantly influences the springback. Currently, the springback value is usually determined based on the experimental data obtained during the process development.

Moreover, minimum plastic deformations resulting in the pipeline cross-section deformation shall be ensured during the pipelines fabrication.

Accounting of the specified deviations is possible when applying advanced numerical methods of 3D mathematical modeling.

It shall be noted that one of the cornerstones of the analytical modeling successful implementation is the adequacy of the applied model that means the mathematical qualitative and quantitative description of a real-life physical object with all the constraints, assumptions and boundary conditions. Traditionally, within the framework of the flight-type engines’ common design and manufacture practice, the analytical studies were carried out mainly to analyze working processes in the liquid rocket engine units and elements. The design analysis of processes was not carried out, the primary focus was on the process development with registration and subsequent repetition of the achieved parameters and performance. Nowadays, the application of such approach leads to significant loss of time for the process mastering of production and can make the product range non-competitive.

4. Approach to the fabrication and assembly of pipelines applying modern technologies

The modern engineering development stage requires to calculate and model both work and manufacturing processes. As to the pipelines, it is required to model the entire process of their fabrication including the workpiece heat treatment, bending with account for mechanical elastic and plastic deformations of local heatings, warping and buckling failure during fabrication, elastic and residual stresses and deformations, cold-work strengthening, non-uniformity of mechanical properties, etc.

Thus, sophisticated multidisciplinary analytical mathematical models having a high level of compliance with the real-life physical and mechanical properties of materials, product design, running technical and production processes are applied in the course of the pipeline fabrication analytical modeling that take into account the entire scope of affecting factors and loads.

The use of the geometrical model maximally similar to the real-life object is an important requirement. For instance, it is desirable to use the geometrical model developed with consideration of the actual part/assembly unit dimensions in order to analyze the strength characteristics of a particular example.

At the same time, it shall be noted that modern design and production engineering approaches basically handle quite simple hydraulic, thermal, kinematic, static and dynamic (vibration) calculations performed based on simplified geometrical models using averaged (rated) material characteristics. The results are sometimes quite different from the full-scale test results and require the introduction of corrective empirical coefficients that is near impossible when designing new products. Consequently, such analytical models do not allow predicting the products behavior during the entire life cycle with the accuracy required to exclude deviations during the fabrication and testing, and the attempt to do so at the early stages of development, even before the models have become more equivalent to reality, turns into an actual "false start" that hands over the baton of problems/incompliances to the next stages of the product life cycle increasing the costs and expenditures, as well as the overall time of the product launch [5].

A generalized algorithm for applying the modern approaches to the design, fabrication and assembly of pipelines including the application of the object geometric model in the course of the design, fabrication and inspection is shown on Figure 3. This algorithm is rather simplified and may be
amended for each specific case taking into account the fabrication and operation conditions.

![Pipeline fabrication algorithm using the model-centric approach](image)

**Figure 3.** Pipeline fabrication algorithm using the model-centric approach

The application of the specified approach, except for the exclusion of the pipelines adjustment and pre-bending during assembly, will allow to move beyond the typical today's situation when the number of design variations caused by the introduced errors or new data is evenly distributed over the entire life cycle starting from the design and to the production and fabrication preparation. It is a common knowledge that the later the variations are introduced, the higher is the cost of their implementation. With the model-centric approach it becomes possible to transfer the majority of variations to the design stage (in this case, the "design" stage includes the 3D model obtained based on the results of measuring the actual spatial geometry of the junction points) and minimize the costs of the variations introduction and implementation. In addition, the use of such method will allow to eliminate the "human factor" in the course of the pipelines fabrication and engine assembly.

It should be noted that the pipelines design in the form of the electronic design documentation included in the engine electronic model is of crucial significance for the application of the advanced pipeline fabrication and inspection methods and may be implemented in the two following ways:

- development of the electronic model by reproducing the reference pipeline;
- pipeline development based on the product electronic model.

The first method may be used for the engines produced in series or the engines that already have reference pipelines. Such a model for ensuring the assembly without modifications is required to be adjusted to the engine digital model developed as per the nominal dimension values. With this method the reference pipeline is digitized with the help of a 3D scanner receiving a point cloud. Then, a route is constructed based on the received data along which the pipeline cross-section is constructed. The main disadvantage of this method is that the obtained pipeline model will correspond not to the nominal dimensions, but to the dimensions of the particular engine with all its deviations and mismatches. The main advantage lies in the fact that it is not required to develop an electronic model of the entire engine to start the work, i.e. one can get to work immediately upon taking the decision on digitalization.

The second method is applicable for the products being designed. The route is constructed based on
the engine electronic model using the basic connecting points and the influence of all elements included in the electronic model. The main advantage of this method is the obtaining of the pipeline model developed as per the nominal dimensions taking into account all the constraints imposed by the designer requirements, as well as the possibility of optimization due to the analytical modeling in parallel with the design. The main disadvantage is that this method requires the development of the complete electronic model of the entire engine.

Both the first and the second methods of obtaining the pipeline electronic models may be used depending on the engine development stage, requirements to its elements, availability of instrumentation equipment.

5. Conclusions
The above approach represents one of the steps in utilizing the product "digital twins" - a complete mathematical description of not only the generalized, "ideal" product, but also of each particular example with its inherent geometrical, hydraulic, strength, thermal and other parameters and performance.

Thus, the task of installing the liquid rocket engine pipelines with no adjustments and modifications is an integrated task combining the design, inspection and fabrication issues. The application of state-of-the-art design, inspection and fabrication tools based on the use of the model-centric 3D computer modeling allows to address the solution of the issue of installing the pipelines with no adjustments.

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