About application of NURBS to monitoring of operational risk of long distance pipelines

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About application of NURBS to monitoring of operational risk of long distance pipelines

A.S. Galakhar
Associate Professor,
The School of Computer-driven Systems of Manufacturing Automation,
Faculty of Robotics and Integrated Automation,
Bauman Moscow State Technical University, bldg. 5, 2-nd Baumanskaya St.,
Moscow, 105005, Russia

E-mail: a.galakhar@bmstu.ru

Abstract. The system of monitoring of operational risk of long distance pipelines requires determining the actual safety factor in real time for instant evaluation of accident risk.

The actual safety factor of a pipeline section is determined for not only technical condition of pipes in the section which is assessed using data of periodic inspections, but also for actual distribution of pressure of pipeline transported medium. Degradation results in slow change of pipeline technical condition. Therefore, the actual safety factor of the operated pipeline depends mainly on loads exerted on the pipe, particularly the load from internal pressure which depends not only on the inlet pressure of the pipeline section, but also on the terrain where the pipeline lies, the actual position of the pipeline in the area and the actual varying conditions of heat transfer from the transported medium to surrounding environment through the pipeline wall.

The actual pressure distribution in the pipeline section is determined from the differential equation of motion of the transported medium, which is solved using non-uniform rational B-splines (NURBS) and the data of real time temperature measurements.

1. Introduction
The wide spread approach to evaluation of technical condition of a pipeline on the basis of stress-strain properties of materials and design data of operating pipes allows identification of its compliance with the requirements of engineering documentation, but does not allow answer the question of safety of continuing operation of the pipeline. The measure of safety of an operating pipeline is risk. The notion of risk was defined differently in various studies devoted to value of risk [1-4]. The risk of continuing operation of a long distance pipeline comprehends accident risk.

Accident risk is the measure of danger describing the probability of accident initiation at hazardous production facility and the severity of the consequences corresponding to it [5, 6].

The accident risk can be managed via reducing its two components [7]:
1) the probability of failure or crashworthiness of the pipeline;
2) accident damage actual or possible.

The possibility of continuing operation of a hazardous production facility is determined via acceptable risk indicated in the declaration of industrial safety. Therefore, the risk must be controlled during operation [7].
Monitoring of operational risk of such hazardous production facility as a long distance pipeline is required for implementation of risk-oriented approach to control and supervisory activity of the government relying on new information technologies of accident prevention at reduced number of periodic inspections [8]. Adoption of the risk-oriented approach to supervisory activity has been already reflected in state standard [9].

To avoid exceeding of admissible operational risk, the pipeline would be maintained on the basis of real-time prognostic modelling of its technical condition using telemetry data [10, 11]. The corresponding models for real-time risk assessment and prediction would be simple, optimally taking the operating conditions into account and allow for measurement uncertainty to be used in the decision making process [10].

The real-time operational risk assessment would consider not only design factors, defects of pipeline wall and variation of material properties, but also loads that govern actual safety factor and accident risk of the pipeline [12].

The stress intensity in a pipeline wall is determined mostly by pressure and temperature of cargo medium. However, the limited capability to measure the strains of pipeline wall, pressure and temperature of cargo medium all along the pipeline makes necessary to resort to modelling of these quantities in real time. Such modelling requires attaining the analysis accuracy comparable with the accuracy of measurements during the shortest possible time.

Nevertheless, researchers do not attend the performance of mathematical models of flow in the long-distance pipelines at the present time. So, the model based on finite-difference mesh was proposed for numerical simulation of flow of viscous media in the pipelines with connections of irregular shape [13]. The model based on Runge-Kutta method was proposed for solution of three differential equations for gas flow [14]. The numerical solution of differential equations with the finite difference of Runge-Kutta method requires a prior construction of geometrical approximation of the pipeline where the solution is sought in separate points that causes increase in computing efforts.

The non-uniform rational B-splines (NURBS) are widely used for geometric modelling in modern real-time applications [15]. Consequently, monitoring of accident risk of operating pipeline would advantage from isogeometric analysis [16], which allows not only giving the geometrical approximation up, but also reducing the number of unknowns in the analysis of required accuracy.

2. Modelling of oil flow in a pipeline

2.1. Presentation of pipeline axis in space

The pipeline axis is presented using a spatial NURBS curve. The points of the NURBS curve are described with a radius-vector \( \mathbf{C}(u) \) with coordinates determined from equations (1).

\[
\begin{align*}
    x(u) &= \frac{\sum_{i=0}^{n} N_{i,p}(u) w_i x_i}{\sum_{i=0}^{n} N_{i,p}(u) w_i}, \\
    y(u) &= \frac{\sum_{i=0}^{n} N_{i,p}(u) w_i y_i}{\sum_{i=0}^{n} N_{i,p}(u) w_i}, \\
    z(u) &= \frac{\sum_{i=0}^{n} N_{i,p}(u) w_i z_i}{\sum_{i=0}^{n} N_{i,p}(u) w_i},
\end{align*}
\]

where \( x_i, y_i, z_i \) are spatial Cartesian coordinates of \( i \)-th control point of the NURBS curve; \( N_{i,p}(u) \) is \( i \)-th basis function of the NURBS curve of degree \( p \); \( w_i \) is the weight of \( i \)-th control point of the NURBS curve.

The values of the basis functions of the NURBS curve of degree \( p \) are determined by formulae (2).

\[
N_{i,0} = \begin{cases} 
1 & \text{если } u_i \leq u \leq u_{i+1}, \\
0 & \text{иначе,}
\end{cases}
\]

\[
N_{i,p}(u) = \sum_{k=0}^{p} \binom{p}{k} \left( \frac{u-u_i}{u_{i+p}-u_i} \right)^k \left( \frac{u_{i+p}-u}{u_{i+p}-u_{i+1}} \right)^{p-k} N_{i,p-k-1}(u),
\]

where \( \binom{p}{k} \) is the binomial coefficient.

\[\]
where \( u_i \) is the component of a knot vector \( \vec{U} = \{0, \ldots, 0, u_{p+1}, \ldots, u_{m_u-p-2}, 1, \ldots 1\} \) of dimension \( m_u = n + p + 2 \).

The minimal degree of a general NURBS curve with non-zero torsion in 3D space is \( p = 3 \), and it is advantageous for presentation of a pipeline axis in isogeometric modelling, as it gives the matrix with the narrowest bandwidth.

The spatial coordinates of the NURBS representation of the pipeline axis can be determined from the data of geodetic survey using known algorithm [17] of the least-squares method.

Curvature and torsion of a spatial NURBS curve can be calculated exactly by the well-known formulae where the parametric derivatives of NURBS can be obtained using known algorithms [17].

2.2. Characterization of cargo medium

2.2.1. A temperature of cargo medium. The distribution of cross-section average temperature of cargo medium along the pipeline axis can be expressed by the formula (3), which allows considering variation in conditions of heat exchange in different parts of the considered pipeline section.

\[
T_{int}(u) = \frac{\sum w_{T,i} n_{ip}(u) w_{T,i}}{\sum n_{ip}(u) w_{T,i}},
\]

where \( w_{T,i} \) is the weight of \( i \)-th control point \( T_{int,i} \) of NURBS representation of distribution of the cross-section average temperature of cargo medium along the pipeline axis.

Both \( T_{int,i} \) and \( w_{T,i} \) are determined by interpolation of measurement data using a NURBS curve of degree \( p = 3 \) with the same knot vector \( \vec{U} \) as the knot vector of NURBS representation of the pipeline axis.

2.2.2. Properties of cargo medium. The NURBS interpolation of such pressure and temperature dependent properties of cargo medium as kinematic coefficient of viscosity \( \nu_{int} \), density \( \rho_{int} \), coefficient of heat conductivity \( \lambda_{int} \) and specific heat capacity at constant pressure \( C_p_{int} \) is determined along the pipeline axis using the known physical formulae for the specific cargo medium from obtained distributions of pressure and temperature interpolated with NURBS curves. All the NURBS curves are defined for the same knot vector \( \vec{U} \).

2.3. A temperature of pipeline wall

The wall thickness-average temperature of the pipeline can be calculated iteratively.

The similarity criteria for computation of the pipe resistance coefficient and the specific coefficient of heat-transfer are determined for the defining temperature of boundary layer obtained either from expression (4) for laminar flow, or taken equal to the temperature of cargo medium.

\[
T_m = \frac{T_{int}(u) + T_m}{2}.
\]

Nusselt number is calculated by formula (5) for laminar flow, or by formula (6) for turbulent flow of cargo medium [18].

\[
\text{Nu} = 0.74 \cdot \text{Re}^{0.2} \cdot (\text{Gr} \cdot \text{Pr})^{0.1} \cdot \text{Pr}^{0.2},
\]

\[
\text{Nu} = 0.023 \cdot \text{Re}^{0.8} \cdot \text{Pr}^{0.4},
\]

where Re is Reynolds number; Gr is Grashof number; Pr is Prandtl number.

Reynolds number is determined from expression (7).

\[
\text{Re}(u) = \frac{4 \cdot \rho_m}{\pi \cdot (D - 2 \cdot t) \cdot \rho_{int}(u) \cdot \nu_{int}(u)}
\]
where \( G_m \) is the mass flow of cargo medium through the pipeline; \( D \) is outer diameter of the pipeline; \( t \) is thickness of the pipeline wall.

The specific coefficient of heat-transfer is calculated from expression (8).

\[
\alpha = \frac{Nu\lambda_{int}}{D-2-t},
\]

(8)

The temperature of the inner surface of the pipeline \( T_{w1} \) is determined from expressions (9), (10):

\[
T_{w1} = T_m + \frac{G_mC_p\Delta t}{\alpha\pi(D-2-t)\sqrt{(\frac{\partial x}{\partial u})^2 + (\frac{\partial y}{\partial u})^2 + (\frac{\partial z}{\partial u})^2}} \text{ for Re}(u) < 2 \cdot 10^3,
\]

(9)

\[
T_{w1} = T_{int}(u) + \frac{G_mC_p\Delta t}{\alpha\pi(D-2-t)\sqrt{(\frac{\partial x}{\partial u})^2 + (\frac{\partial y}{\partial u})^2 + (\frac{\partial z}{\partial u})^2}} \text{ for Re}(u) \geq 2 \cdot 10^3,
\]

(10)

where \( \Delta t \) is a log-average temperature difference obtained by formula (11).

\[
\Delta t = \frac{\frac{\partial T_{int}(u)}{\partial u}}{\ln\frac{T_{int}(u) - T_{w1}}{T_{int}(u) + T_{w1} - T_{w1}}},
\]

(11)

where \( du \) is the difference between the two nearest distinct components of the knot vector \( \bar{U} \).

Therefore, the temperature of the outer surface of the pipeline is found from formula (12).

\[
T_{w2} = T_{w1} + \frac{G_mC_p\Delta t}{\alpha\pi(D-2-t)\sqrt{(\frac{\partial x}{\partial u})^2 + (\frac{\partial y}{\partial u})^2 + (\frac{\partial z}{\partial u})^2}} \cdot \frac{1}{\lambda_w} \cdot \ln\frac{D}{D-2-t}.
\]

(12)

where \( \lambda_w \) is the coefficient of heat conductivity of the pipeline wall.

The actual safety factor of the pipeline is calculated for the thickness-average wall temperature (9).

\[
T_w = \frac{T_{w1} + T_{w2}}{2}.
\]

(13)

2.4. A distribution of pipeline pressure

2.4.1. A flow equation of cargo medium. The distribution of pipeline pressure can be presented using NURBS with the same knot vector \( \bar{U} \) as the pipeline axis (14).

\[
p_{int}(u) = \frac{\sum_{i=0}^{N_{i,p}(u)} w_{int\ i} p_{int\ i}}{\sum_{i=0}^{N_{i,p}(u)} w_{int\ i}},
\]

(14)

where \( w_{int\ i} \) is the weight of \( i \)-th control point \( p_{int\ i} \) of NURBS representation of distribution of pipeline pressure along the pipeline axis. It is assumed, that \( w_{int\ i} = w_i \).

Parametric derivatives \( \frac{\partial p_{int}(u)}{\partial u} \) obtained from equation (14) must also fit equation (15) at any value of parameter \( u \).

\[
-\frac{1}{\rho_{int}(u)} \frac{\partial p_{int}(u)}{\partial u} + \zeta_p(u) \cdot \frac{\beta G_m}{\pi^2(D-2-t)^5} \left( \frac{\partial x}{\partial u} \right)^2 + \frac{\partial y}{\partial u}^2 + \frac{\partial z}{\partial u}^2 \cdot \frac{1}{\rho_{int}(u)^2} + \frac{\beta G_m}{\pi^2(D-2-t)^4} \cdot \frac{\partial}{\partial u} \left( \frac{1}{\rho_{int}(u)^2} \right) + g \cdot \frac{\partial z}{\partial u} = 0,
\]

(15)

where \( \zeta_p(u) \) is the pipe resistance coefficient for cargo medium at the straight portion of the pipeline under pressure \( p_{int}(u) \) and at the cross-section average temperature of \( T_{int}(u) \); \( g \) is the free fall acceleration.

There is delivery pressure or outlet pressure assumed to be measured in the pipeline section.
2.4.2. Control points of pressure distribution. The control points of NURBS representation of pipeline pressure distribution along the pipeline axis are found from iterative solution of system of algebraic equations (16), the right part of which is defined more accurately at each new iteration depending on \(p_{\text{int}}\) obtained, while the difference between two last solutions is greater than the measurement uncertainty of pipeline pressure.

\[
A_p \cdot \hat{X}_p = \hat{B}_p,
\]

where \(A_p\) is the matrix of order \(n \times n\), nonzero elements of which are obtained from equations (17) — (19) for known delivery pressure in the pipeline section, or from equations (20) — (21) for known outlet pressure in the pipeline section; \(\hat{X}_p\) is the vector of NURBS control points \(\hat{X}_p^i = (p_{\text{int}0}, p_{\text{int}1}, ..., p_{\text{int}n-1})^T\); \(\hat{B}_p\) is the vector, components of which are obtained from equations (20) — (21) for known delivery pressure in the pipeline section, or from equations (25) — (26) for known outlet pressure in the pipeline section.

If the delivery pressure is measured, then

\[
a_{pj,j+p+1} = \frac{1}{\sum_{i=0}^{n} N_{i,p}(u_i) w_i} \left[ \sum_{i=0}^{n} N_{i,p-1}(u_i) \frac{p_{\text{int}}(u_i)}{u_{j+p+1}-u_{j+1}} \cdot N_{j+1,p}(u_i) \cdot w_{j+1} + \frac{p_{\text{int}}(u_j) w_j}{u_{j+p+1}-u_{j+1}} \right],
\]

\(j = p, ..., n,\)

\[
a_{pj,j+k} = \frac{1}{\sum_{i=0}^{n} N_{i,p}(u_i) w_i} \left[ \sum_{i=0}^{n} N_{i,p-1}(u_i) (u_{j+k+1}-u_{j+k}) \cdot w_{j+k} + \frac{p_{\text{int}}(u_k) w_k}{u_{j+k+p+1}-u_{j+k}} \cdot N_{j+k,p}(u_i) \right],
\]

\(j = 1, ..., n, k = 0, ..., p - 1,\)

\[
a_{pj,j+p} = \frac{1}{\sum_{i=0}^{n} N_{i,p}(u_i) w_i} \left[ \sum_{i=0}^{n} N_{i,p-1}(u_i) \frac{p_{\text{int}}(u_i)}{u_{j+p+1}-u_{j+1}} \cdot N_{j+p+1,p}(u_i) \right],
\]

\(j = 1, ..., n,\)

\[
b_{pj} = \frac{1}{\sum_{i=0}^{n} N_{i,p}(u_i) w_i} \left[ \sum_{i=0}^{n} N_{i,p-1}(u_i) \frac{p_{\text{int}}(u_i)}{u_{j+p+1}-u_{j+1}} \cdot N_{j+p+1,p}(u_i) \right] \cdot p_{\text{int}0}.
\]

\(j = 1, ..., p - 1,\)

\[
b_{pj} = \frac{1}{\sum_{i=0}^{n} N_{i,p}(u_i) w_i} \left[ \sum_{i=0}^{n} N_{i,p-1}(u_i) \frac{p_{\text{int}}(u_i)}{u_{j+p+1}-u_{j+1}} \cdot N_{j+p+1,p}(u_i) \right] \cdot p_{\text{int}0}.
\]

\(j = 1, ..., n,\)

\[
a_{pj,j} = \frac{1}{\sum_{i=0}^{n} N_{i,p}(u_i) w_i} \left[ \sum_{i=0}^{n} N_{i,p-1}(u_i) \frac{p_{\text{int}}(u_i)}{u_{j+p+1}-u_{j+1}} \cdot N_{j+p+1,p}(u_i) \right],
\]

\(j = 1, ..., n,\)
\[ a_{pj+k} = \frac{1}{\Sigma_{i=0}^{n}N_{ip}(u)w_{i}} \left\{ \left[ \frac{p}{u_{j+k+p-1}+u_{j+k+1}} \cdot N_{j+k,p-1}(u) \right] \cdot w_{j+k} \right\}, \quad j = 1, \ldots, n, \quad k = 0, \ldots, p - 1, \tag{23} \]

\[ a_{pj+p} = \frac{1}{\Sigma_{i=0}^{n}N_{ip}(u)w_{i}} \left\{ \left[ \frac{p}{u_{j+2p-1}+u_{j+p}} \cdot N_{j+p-2,p-1}(u) \right] \cdot w_{j+p-1} \right\}, \quad j = 1, \ldots, n, \tag{24} \]

\[ b_{pj} = \zeta_{p}(u) \cdot \frac{8c^{2}_{m} \gamma_{n}}{\pi^{2}(D-2t)^{4}} \cdot \frac{1}{\rho_{int}(u)} + \frac{8c^{2}_{m} \rho_{int}(u)}{\pi^{2}(D-2t)^{4}} \cdot \frac{\partial}{\partial u} \left( \frac{1}{\rho_{int}(u)} \right) + \]

\[ + \rho_{int}(u) \cdot g \cdot \frac{\partial u}{\partial u} \quad j = 1, \ldots, n - p, \tag{25} \]

\[ b_{pj} = \zeta_{p}(u) \cdot \frac{8c^{2}_{m} \gamma_{n}}{\pi^{2}(D-2t)^{4}} \cdot \frac{1}{\rho_{int}(u)} + \frac{8c^{2}_{m} \rho_{int}(u)}{\pi^{2}(D-2t)^{4}} \cdot \frac{\partial}{\partial u} \left( \frac{1}{\rho_{int}(u)} \right) + \]

\[ + \rho_{int}(u) \cdot g \cdot \frac{\partial u}{\partial u} \cdot \left[ \frac{1}{\Sigma_{i=0}^{n}N_{ip}(u)w_{i}} \left\{ \sum_{i=0}^{p} N_{i,p-1}(u) \frac{p}{u_{j+i+1}+u_{j+i}} \cdot N_{n,p}(u) \right\} \right], \quad j = n - p + 1, \ldots, n. \tag{26} \]

where \( u \) is the parameter value between two different components of the knot vector \( \vec{U} \).

2.5. A probability of failure

Probability \( Q \) of pipeline failure can be determined from expression (27).

\[ Q = \Phi(-U_{p}), \tag{27} \]

where \( U_{p} \) is the fractile of normal distribution for probability \( P \) of no-failure, that is determined by formula (28) [12, 19].

\[ U_{p} = 3.1 \cdot \frac{k_{p}^{p-1}}{\sqrt{k_{p}^{p} \left( 1-k_{a} \right)^{2} + (k_{e}-1)^{2}}} \tag{28} \]

where \( k_{p} \) is ultimate factor of pipeline safety; \( k_{u} \) is coefficient of uniformity; \( k_{e} \) is overload factor.

The actual ultimate factor of safety of operating pipeline can be determined from expression (29).

\[ k_{p} = \frac{\sigma_{u}}{\sigma_{l}}, \tag{29} \]

where \( \sigma_{u} \) is the ultimate stress of the pipeline; \( \sigma_{l} \) is the working stress intensity in the pipeline wall, that can be found using standard method [20].

The coefficient of uniformity is calculated from expression (30).

\[ k_{u} = \frac{1}{k_{l}}, \tag{30} \]

where \( k_{l} \) is the material safety factor from table 10 [21].

The overload factor is obtained from formula (31).
\[ k_e = \frac{n_p k_r}{m}, \]  

(31)

where \( n_p \) is load safety index from table 14 [21]; \( k_r \) is index of reliability significance from table 12 [21]; \( m \) is the coefficient of pipeline operating conditions from table 1 [21] for analysis of pipeline strength, buckling resistance and dimensional instability.

3. Probability of failure of a pipeline assessed from telemetry data

3.1. The specification of the pipeline section

The probability of failure was assessed for pipeline section shown in figure 1. The outer diameter of the pipeline is 813 mm. The pipeline is made of steel 13Г1С-У. The wall thickness of pipes is 11.9 mm. The temperature of pipe laying was +5 °C.

![Figure 1. The pipeline section.](image)

The pipeline is used for transmitting cargo oil. Physical properties of the oil are given in table 1.

| Property                        | +15 °C   | +20 °C   |
|---------------------------------|----------|----------|
| Density, kg/m³                  | 848.8    | 844.8    |
| Kinematic viscosity coefficient, m²/s | 8.3 \( \cdot \) 10^{-6} | 7.3 \( \cdot \) 10^{-6} |

In the considered point of time mass output flow of oil-transfer pump No. 8 was 419.5 kg/s, the oil temperature was +9.6 °C, the delivery pressure was 3.77 MPa. At suction of oil-transfer pump No. 9 the oil temperature was +9.0 °C, the pipeline pressure was 2.98 MPa.

3.2. The calculated distribution of pipeline pressure and maximal stress intensity

The calculated distribution of pipeline pressure is shown in figure 2. The pipeline pressure increases, when the altitude of pipeline axis above sea level descends, and generally decreases along the pipeline. The outlet pressure of the pipeline section obtained from analysis is 2.94 MPa which corresponds with the measured pressure at suction of oil-transfer pump No. 9 within uncertainty of measurements.

![Figure 2. The pressure profile.](image)
The pressure distribution obtained from calculated outlet pressure coincides with the pressure distribution obtained from delivery pressure measured at oil-transfer pump No. 8 within calculation accuracy.

The diagram of working stress intensity in the pipeline section (figure 3) obtained for the calculated distribution of pipeline pressure and interpolation of oil temperature follows the diagram shown in figure 2. However, the fractional variation of working stress intensity is smaller than such variation of pipeline pressure because of the effect of thermal expansion on stress-strain state of the pipeline.

![Figure 3. The stress intensity profile.](image)

3.3. The calculated actual ultimate safety factor and probability of failure of operating pipeline

The actual ultimate safety factor of operating pipeline made of steel 13Г1С-Y ($\sigma_u = 620$ MPa) changes with pipeline pressure from 3.29 to 4.16 as shown in figure 4. The diagram demonstrates that the actual ultimate safety factor is more sensitive to change of pipeline pressure than the stress intensity (figure 3).

![Figure 4. The profile of actual ultimate safety factor.](image)

The relation between probability of failure and actual ultimate safety factor is highly nonlinear. Therefore, the change of pipeline pressure in 1.7 times results in change of probability of failure by two orders of magnitude (see figure 5).

![Figure 5. The profile of probability of failure.](image)

4. Conclusions

The proposed method of assessment of probability of failure of operating pipelines includes both heat exchange and pipeline strength analysis based on telemetry data about pipeline pressure and temperature of cargo medium. The NURBS representation of pipeline axis obtained from design documentation or geodetic survey is used for analysis directly without necessity of building a discrete geometrical model. Such approach simplifies and accelerates the analysis.

A pipeline is a thermally thin body and its temperature is determined during operation mostly by the temperature of cargo medium.

Accuracy of the NURBS based analysis of distribution of pipeline pressure is comparable with the accuracy of measurements, that allows using it for monitoring of operational risk of long distance pipelines for assessment of accident risk and maintenance check of manometers in use.

The high sensitivity of probability of failure to pipeline pressure allows guarantee of pipeline safety at the cost of reduction of delivery pressure in case of urgent need.
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