Proposal Of Simplified Way of Applying Wind Load on Circular Cross-Section

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Abstract. Wind action on circular cross section was described in many publications. It finds an application for flue gas ducts, pipelines, silo or chimneys. This study concentrate on elements with diameter greater than 1m. There are well recognized analytical solutions of static calculation with uses Fourier-series for wind distribution. Although during last 10 years numerical methods of solving problems get more popular, especially among young engineers. For surface structures ability of analytical finding internal forces disappears, and Finish Element Method substitutes analytical calculation. Modelling of wind load in FEM programs cause several problems. Using wind load distribution proposed in Eurocode 1-4, or from laboratory test, it is usually necessary to divide circular cross-section into 32 up to 72 rectangular elements. Applying load in that way is the most accurate method to imitate wind load in FE model. From the other hand that take much time, and requires preparing data about distribution before modelling. Applying wind on complicated model, with many independent parts of piping, for at least 2 load cases cause faults and slows down work. This paper shows and compares a few proposal wind load models for numerical calculation. Those models were built to obtain accurate internal forces in compare to Eurocode procedure. Proposed models offers simplification of Geometry in numerical model, and saves of time. It also helps to make FE mesh become independent from structural nodes, lines or divisions. This paper concern on one case of one Reynolds number, with refers to 2m wide cylinder, wind velocity of 22m/s and surface roughness of steel plate – 0,05 mm. This paper compares different wind load distributions, in terms of required number of division of model, time consuming, precision of results. Author selected on proposal load distribution, with give equivalent internal forces as wind load distribution obtained from Wind Flow simulation (for example CFD method). Proposed model is useful for structural engineers and statics in offer stage of project. With some safety factor it can be also used as wind load as case for detailing cylindrical structures.

1. Introduction
Wind load action on circular cross-section was already well recognized [1]. Wind load distribution around section is known, and it, depends on Reynolds number, so the Diameter of cross-section, wind speed and surface roughness. Distribution of load, can be described by Fourier series or curve defined by series of points.

European norm [2] recommends to read wind load distribution for circular cross-cross-section from graph. This process is quite complicated and requires significant amount of time. It is also not very precise, because there are given curves only for 3 different Reynolds numbers (with vary from $5 \cdot 10^5$ to $10^7$).
Nowadays FEM method are the most popular way to determine internal forces in circular structures. There are also methods of finding internal forces basics on analytical solution. Unfortunately, those are getting forgotten, mostly among young engineers. FEM dominates all another methods.

In modelling structure in FEM software, it is complicated and time consuming to apply wind load according to Eurocode. Discretisation of load, requires dividing the model, before calculation start. From the beginning of calculation FE Mesh depends on decision made before calculation. Some engineering software, allows to define load by whichever curve, although those function have some limitation.

Dividing model and applying load independently on each panel gives the most accurate results. This indicates some problems in early steps of designing process, because it requires building very accurate model from the beginning.

This paper will show some alternative load distributions, that will gave similar internal forces (necessary to design shell) on structure. Those method do not provide more accurate calculation although it simplifies engineer work.

2. Assumptions and methods
This study concentrate on one case of geometry and one wind flow parameters. Wind load distribution was tested for circular pipe with diameter of 2m and length 20m (16m between supports). Equivalent roughness for bright steel, according to Table 7.1 in norm [2] is equal to 0,05mm. Study assume, that analyzed structure is located on flat area, bellow 300m over sea level. wind zone – 1, and II category of terrain base wind velocity is equal 22m/s. Piping system are usually located on some substructures a few meters over ground, so height of structure is assumed as 10m for wind pressure calculation.

According to procedure given in Eurocode [2], equation (4.8), obtained peak velocity pressure is equal to 0,705kPa. Roughness parameters can be obtained using procedure given in 7.9.1 in Eurocode [2], or literature [1]

\[ v(z) = \sqrt{2 \cdot \frac{q_\rho(z)}{\rho}} = \sqrt{2 \cdot \frac{705}{1.25}} = 33.59 \text{ m/s} \] (1)

\[ Re = b \cdot \frac{v(z)}{\nu} = 2 \cdot \frac{33.59}{15 \times 10^{-6}} = 4.478 \times 10^{-6} \] (2)

Where the viscosity \( \nu \) is equal to 15\( \times 10^{-6} \) m\(^2\)/s.

The factor \( c_{p0} \) obtained for different angle \( \alpha \) is presented in table below.

| \( \alpha \) | 0  | 10  | 20  | 30  | 40  | 50  | 60  | 70  | 80  | 90  | 100 | 110 | 120 | 180 |
|----------|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| \( c_{p0} \) | 1  | 0.830 | 0.517 | 0.074 | -0.40 | -0.88 | -1.30 | -1.57 | -1.69 | -1.59 | -1.34 | -0.94 | -0.78 | -0.78 |

a)Intermediate values were obtained by linear interpolation.
In this study Finish Element Method (FEM) were used. Loads are being analyzed in two steps. First, there were analyzed loads on 2D models – on plane cross-section of duct. Selected wind load distribution, with fulfill expectations in 2D analysis, were tested on 3D model of total part of flue gas duct.

In the first step were analyzed only bending moments, deflection and stresses ($\sigma_{HMH}$). Two cross sections were took into account – cross-section in the middle of the duct (section 2-2 in Figure 2), between supports and cross section in supporting plane (section 1-1 in Figure 2). Due to shape of supports, sections 1-1 and 2-2 must be supported in different way. Horizontal support, perpendicular to duct normal axis is located in the bottom of duct – in the middle or on the one of supporting legs.

![Figure 2. Static scheme of 2D sections. Section 1-1→section on support (geometrical view and static scheme), Section 2-2 →section in the middle of the duct. Dimensions in mm](image)

Analysis in second step basics on 24m long 3D models of duct (as shown in the Figure 3). Diameter of duct is 2m, the same as in case of 2D model. Distance between supports is 20m. In addition there is perpendicular ribbing located in the section 1-1 and in the both ends of the duct. Those ribs are necessary due to structural reasons.

![Figure 3. Calculation model of duct](image)
2.1. Substitutional wind load
In this study a few wind load cases were analyzed. Below are presented load distribution factors for analyzed cases. First one, presents distribution obtained from Eurocode [2]. The other one presents proposal wind factors $c_{pe}$. Wind load acting on circular pipe can be obtained by equation (3). (Figure 4)

$$w = c_{pe} q_p(z)$$  \hspace{1cm} (3)

Where:
- $w$ – wind load acting locally on surface
- $c_{pe}$ – wind load factor
- $q_p(z)$ – peak wind velocity.

![Figure 4. graphical presentation of distribution of wind load factor - $c_{pe}$ on surface](image)

3. Finite Element calculation – 2D models
3.1. Wind load according to Eurocode [2],
It is recommended, to divide circular sections into (36÷72) finish elements (FE) in direction of rotation. Mesh finer than 72FE do not increases accuracy of calculation, but make calculation more difficult and may cause some numerical inaccuracy. In this study basic model was divided in 36 FE. Influence of mesh density on results was analyzed by many scientists, including author of following article, in study [3].
Pipes can be modeled as a multiple number of rectangular panels or a few (or even one) curved panel. For pipes modeled with rectangular panels, FE mesh is automatically connected with the count of panels. There is no sense to refine the mesh, because additional nodes would not be located on pipe surface, as shown in figure 5. In case of modeling circular shapes using curved panels it is obligatory to use refinement of mesh.

![Figure 5. FE nodes on surface of pipe](image)

3.2. Substitutional wind load
Wind load were tested on two static schemes, as shown in Figure 1. Calculation was performed with engineering software- RFEM Dlubal. Support system assumed for calculation is presented in Figure 6. Section of pipe consist of 36 equal members. Flat bar with cross-section of plate 5×1000mm imitate 1 m long part of the pipe. Distribution of the load acting on the structure is presented in Chyba! Nenalezen zdroj odkazů.

![Figure 6. Support system in 2D calculation model. a) intermediate section, b) support section](image)
Figure 7. Models of load applied on structure calculated for wind pressure $q_p(z) = 0.705\text{kPa}$. Picture a) shows standard pressure distribution.
Shapes of pressure are proposals created for this study. Values of pressure coefficient were defined with trial and error method, to obtain results similar as for standard pressure distribution shown in a), Figure 8.

3.3. Results
Figure below presents reactions and bending moments obtained for standard distribution of pressure (as shown in the picture a) Figure 7. Reactions and bending moments obtained for proposal cases are presented in the Figure 9

![Figure 8](image-url)

**Figure 8.** Reactions [kN] and bending moments [kNm]: a) intermediate and b) support section.

a) – proposal 1 – section 2-2  

b) – proposal 1 – section 1-1  

c) – proposal 2 – section 2-2  

d) – proposal 3 – section 2-2  

e) – proposal 4 – section 2-2  

f) – proposal 5 – section 2-2
g) – proposal 6, section 2-2  g) – proposal 6, section 1-1

Figure 9. reactions [kN] and bending moments [kNm] obtained from calculation for selected cases

Diagram of bending moments presented in the Figure 8, a) have local extremes – in the front and in the top and bottom. Proposal pressure distributions should give similar distribution of bending moments, values of bending moments and the same reaction as shown in the Figure 8. Eurocode 3 [4] provides method of detailing of thin wall pipes. Four limit states should be checked (LS1, LS2, LS3, LS4). For static loads, limit states LS1 (limitation of stress) and LS3 (buckling of shell) are usually crucial. Excepting wind load, there are also gravity load and internal pressure acting on surface of pipe. In case of linear static, results of each case can be superpose. So it is important to obtain similar values and also shape of bending moment on diagram for proposal wind loads, because different load cases may give extreme internal forces in different locations.

Comparison of results (presented in Figure 8 and Figure 9) obtained for all cases and sections is presented in table below. Proposal loads 3 and 4 were rejected, because it provides different bending moments, than expect. Proposal 2 imitates standard wind load the best. However, to ensure, the proposal distribution of pressure give correct internal forces, there is need to test proposals on 3D model. Due to huge length of analyzed geometry of structure in compare to its diameter, structure behave similar to free supported beam. In the pipe occurs normal stresses parallel to the main axis of the duct.

Table 2. Reaction and extreme bending moments obtained from 2D static analysis

| Distribution of pressure | Sum of horizontal reactions | Section 1-1 | Section 2-2 | comments |
|--------------------------|----------------------------|-------------|-------------|----------|
|                          |                            | max         | min         | max       | min       |
| H, [kN]                  |                            | m_{max}, [kNm] | m_{min}, [kNm] | m_{max}, [kNm] | m_{min}, [kNm] |
| Eurocode                 | 1.003                      | 0.252       | -0.257      | 0.23       | -0.201    | Standard |
| Proposal 1               | 1.008                      | 0.256       | -0.257      | 0.23       | -0.232    |          |
| Proposal 2               | 1.010                      | 0.255       | -0.253      | 0.232      | -0.200    |          |
| Proposal 3               | 1.008                      | 0.120       | -0.120      | 0.020      | -0.020    | Incorrect shape of bending moments |
| Proposal 4               | 1.008                      | 0.129       | -0.146      | 0.081      | -0.074    | Incorrect shape of bending moments |
| Proposal 5               | 1.008                      | 0.254       | -0.271      | 0.231      | -0.211    |          |
| Proposal 6               | 1.008                      | 0.229       | -0.24       | 0.229      | -0.24     |          |
4. Numerical calculation on 3D model

4.1. Calculation model and assumptions
The 3D model was built in this stage, to find crucial internal forces and stress in the structure. Models are free supported – model assume rotation on support. Structure with mesh and support system are presented on Figure 10. Inlet and outlet ribbing was modeled as flat bar 8×80mm. Ribs in below supports were modeled as section IPE 120. Each bar connected with shell was modeled with offset equal to half of height of rib. Mesh element size is fixed to 0.17m, so section is divided on 36 elements.

In support sections special “Stiff” elements were used to connect supporting points. In the end of stiff bars are located hinges with possibility of translation along member, and rotation. Stiff ribs are connected and supported in the middle point, to eliminate possible lock of rotation in the support.

Figure 10. Numerical 3D model of structure.

4.2. Results of calculation for standard wind model
Figures below presents the deformation and membrane equivalent stresses in pipe shell. Distribution of internal forces is significantly different than in 2D model. Wind load cause ovalization of duct. Crucial stresses for limit state LS3 are located in the middle of duct. Stresses above support are crucial for limit state LS1. Bending moments in middle section differs with those obtained from 2D model, because of influence of much stiffer supporting ribbing. To imitate situation analyzed in 2D model, distance between supports should be at least 5times greater, with is not possible due gravity loads, so that case is not analyzed in following study. (Figure 11, 12)

Figure 11. deformation of structure

Figure 12. Equivalent, middle stresses – $\sigma_{\text{HMH}}$ [MPa]
4.3. Comparison of stresses for proposal models of load

The greatest and crucial internal forces occurs in the middle of the duct and in support section. For each analyzed proposal of load, the greatest values were compared in the table below.

**Table 3. Comparison of results compared in one table**

| Case         | bending moments | compressive forces | stresses          |
|--------------|-----------------|--------------------|-------------------|
|              | $M_y,max$       | $M_y,min$          | $n_y,max$         | $n_y,min$         | $\sigma_{n,HMH}$ | $\sigma_{HMH}$ | $\sigma_{2,min}$ |
| Eurocode     |                 |                    |                   |                   |                   |               |               |
| Proposal 1   | 0.0724          | -0.0632            | 46.85             | -64.91            | 1.212             | 2.206         | -13.0          |
| Proposal 2   | 0.0534          | -0.0704            | 53.99             | -69.68            | 1.340             | 1.965         | -14.1          |
| Proposal 5   | 0.0703          | -0.0324            | 42.21             | -59.72            | 1.183             | 2.288         | -13.3          |
| Proposal 6   | 0.1260          | -0.048             | 45.18             | -63.93            | 1.264             | 3.189         | -11.9          |
| [kNm/m]      | [kN/m]          | [MPa]              |                   |                   |                   |               |               |

5. Conclusion

Results obtained from 3D calculation show differences between models more than 2D calculation. Those differences may be caused by man factors, like Stiffness of ribbing, dimensions of structure or roughness of surface. However it is possible to obtain crucial stresses using one of proposal wind load distribution – Proposal 1, 2 or 5.

Proposals 3 and 4 do not give internal forces similar to standard model. Proposal 6 offers wrong values of stresses. Those proposals should be rejected.

Simplified wind load should be accurate enough to estimate internal forces in early stage of design. Nevertheless, in detailing stage, it is recommended to use wind load distribution as specified in Eurocode.

References

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