Chapter 2
On the Real Time Tightness Measurement of Complex Shaped Flanges

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Abstract The tightness of a flange is a time-varying variable and depends on the current state of the structure. For obvious reasons, this could be a critical and important information. It would be desirable to get such information in real-time.

In this extended abstract, an example of a flange with 12 bores is used to give a numerical proof that this may be possible in principle. With the help of special trial vectors for a small sliding contact area, so-called contact modes, the tightness state of a joint can be reconstructed based on strain measurements. This is possible within a fraction of a second. This offers the possibility for corrective actions when a critical condition regarding tightness is detected.

Keywords Flange tightness · State monitoring · Virtual sensor

Introduction

Loads and vibrations cause deformations in the contact area of flanges and these deformations obviously affect the tightness. In the worst case, the tightness is no longer guaranteed and the system leaks. The possibility of monitoring leak tightness of flanges in real-time can therefore be a significant improvement to such systems. Through numerical simulation and experimental studies, it is well documented in the literature that the gap and pressure distribution in a contact area are complex functions of the state, see for example [1] and [2]. The existing options for assessing tightness are only moderately suitable for dynamically loaded structures. Static pressure films can be clamped between the contacting surfaces. After the pressure has been applied, the bolts must be loosened again, the film is removed, and the color change is evaluated because it is a measure of the pressure. These films are suitable for assessing the tightness according to the pre-tensioned bolt, but not for permanent monitoring. In [2], a foil is used that must be clamped between the contact surfaces. The sensor is based on a material whose electrical properties are pressure dependent. The foil is divided into cells and the contact pressure can be determined for each individual cell. This technology seems suitable in principle for contact and leak monitoring, but there are some disadvantages: (1) Since the foil must be clamped, the behavior of the joint changes. (2) It is questionable how pressure and heat resistant the foil is - important questions for practical use. (3) Another question is whether such films can be used for very large flanges, such as those required for pipes with a diameter of 1m and more.

In this project it was numerically investigated whether it might be possible to compute the gap distribution with a few strains outside the flange contact area. The magnitude of the strains must be within a measurable range and the result must not be too sensitive to noise.

This extended abstract is organized as follows: The first section gives an idea about the theory which is applied in the following section to a flange contact with 12 bores. The results are investigated with respect to the strain magnitudes and its sensitivity with respect to noise. The full paper can be found in [3].

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Brief Outline of the Theory

Only the idea of the theory is outlined below. The detailed derivation can be found in [3]. It is assumed that a usable FE model of the structure including the flange area is available. With the use of proper trial vectors (commonly called "modes"), the normal displacement (= gap) between the two contact surfaces can be computed in the form of

$$\mathbf{g} = \boldsymbol{\Phi}_g \mathbf{q} \tag{1}$$

where the $(C \times 1)$ vector $\mathbf{g}$ holds the normal distance of all node-to-node contact pairs which form the contact area. The $(C \times Q)$ matrix $\boldsymbol{\Phi}_g$ holds in its columns the portion of the modes which belong to the gap area and the $(Q \times 1)$ vector $\mathbf{q}$ holds the scaling factors (commonly called "modal coordinates") of the modes. It is obvious that the mode base must be able to capture global structural deformations like vibrations and very local ones like the deformations in the contact area. This can be ensured by extending proven mode bases with so-called contact modes. This allows both types of deformation to be represented with sufficient accuracy. For more information on contact modes, the interested reader is referred to [4]. Regarding linear strains, the relation

$$\boldsymbol{\varepsilon} = \boldsymbol{\Phi}_\varepsilon \mathbf{q} \tag{2}$$

also apply where the $(E \times 1)$ vector $\boldsymbol{\varepsilon}$ holds all potential strain measurements at E positions on the structure. The $(E \times Q)$ matrix $\boldsymbol{\Phi}_\varepsilon$ maps the modal coordinates to the strains. By the use of the pseudo inverse equation (2) can be rearranged and plugged into (1) so that

$$\mathbf{g} = \mathbf{G}\boldsymbol{\varepsilon} \tag{3}$$

with the $(C \times E)$ matrix

$$\mathbf{G} = \boldsymbol{\Phi}_g {\boldsymbol{\Phi}_\varepsilon}^\dagger \tag{4}$$

is obtained. Relation (3) is not useful because it holds all potential strain gauges which is far too much for practical use. Training data is used to reduce the number of strain gauges. We assume that, for example through simulation, T training data $\boldsymbol{\varepsilon}_1$ to $\boldsymbol{\varepsilon}_T$ are available. They are arranged column by column in the $(E \times T)$ matrix $\mathbf{E}_T$. In a next step Proper Orthogonal Decomposition (POD, see exemplarily [5]) is used to extract a S dimensional subspace which optimally approximates all T training data in an Euclidian sense. The S vectors which span the subspace are arranged column wise in a $(E \times S)$ matrix $\mathbf{E}_S$. Now the Discrete Empirical Interpolation Method (DEIM, see exemplarily [6]) can be used for a somehow optimal extraction of S sensor positions out of E potential ones. The application of DEIM to $\mathbf{E}_S$ gives a $(S \times E)$ matrix $\mathbf{B}^T$ and a $(E \times S)$ matrix $\mathbf{E}_D$ with the properties

$$\boldsymbol{\varepsilon}_D = \mathbf{B}^T \boldsymbol{\varepsilon} \tag{5}$$

and

$$\boldsymbol{\varepsilon} = \mathbf{E}_D \boldsymbol{\varepsilon}_D. \tag{6}$$

Note, that in relation (5) the $(S \times E)$ vector $\boldsymbol{\varepsilon}_D$ holds a S dimensional subset of the entries in $\boldsymbol{\varepsilon}$. Consequently, $\mathbf{B}^T$ selects the actual used sensors out of all potential ones. The matrix $\mathbf{E}_D$ in relation (6) is used to computed all potential strains on the base of the selected subset stored in $\boldsymbol{\varepsilon}_D$. When (6) is plugged into (3) the final relation

$$\mathbf{g} = \mathbf{G}_D \boldsymbol{\varepsilon}_D \tag{7}$$

with the time invariant $(C \times S)$ matrix

$$\mathbf{G}_D = \mathbf{G}\mathbf{E}_D \tag{8}$$

is obtained. Relation (7) can be used to compute the gap distribution $\mathbf{g}$ based on the strain measurements in $\boldsymbol{\varepsilon}_D$.

Numerical Example

The proposed method is tested on a purely numerical example. The aim is to give a kind of numerical prove that the deformation state of a joint, and thus the tightness, can be determined using just a few strain gauge measurements. As shown in Fig. 1, two pipes are connected with a flange. The dimensions and all other relevant parameters can be found in [3]. The two flange rings are connected via 12 bores (M20 screws). The entire structure is rigidly mounted on one side and 3 forces are applied on the other side (F_x, F_y and F_z). The FE model consists of 131040 linear hexahedron elements and 179162 nodes. The contact surfaces of the flange are congruently meshed with 7944 (= C) node pairs. The contact pressures and the friction forces are computed by nonlinear penalty laws which can be found [3].

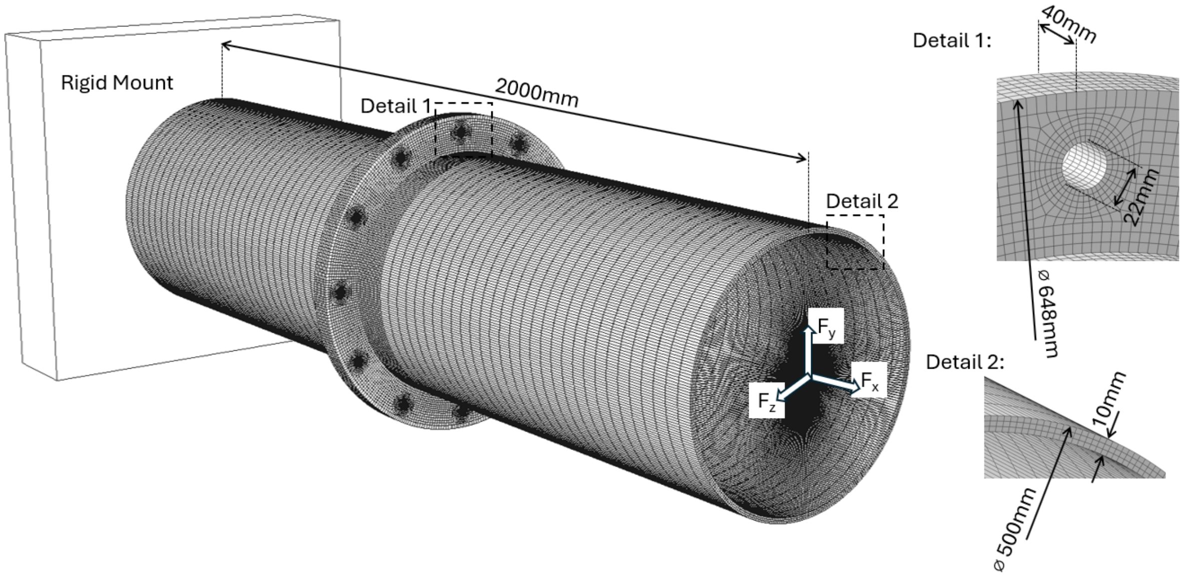

Fig. 1 Pipe structure with flange

Fig. 2 shows the positions of all potential strain measurements. The labeling of each position with two directions is intended to indicate that the strains in these two directions can be measured. The bolts are also fitted with a strain gauge so that the bolt strain can be measured in the longitudinal direction. In sum, this are 156 ($= E$) potential sensor positions.

The potential of the presented method is numerically tested based on non-linear computations which serve as reference solutions. The results of these non-linear computations are the normal distances in the contact area (= gap) as well as the strains at the sensor positions. Based on these strains, the gap in the joint is then reconstructed using the proposed method and then compared with the actual gap from the reference computation. The details of the nonlinear computation can be found in [3]. For the sake of testing 120 load cases are constructed using random numbers for the forces F_x, F_y and F_z. A constant bolt load is acting in all cases. For the construction of $\mathbf{E}_T$, 600 training load cases have been created via the same procedure. For more details on the test and training sets, see [3].

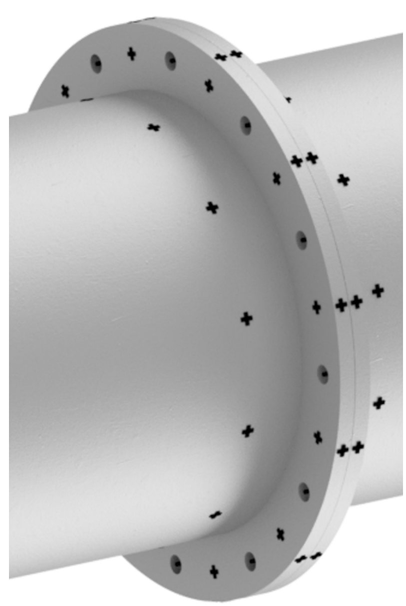

Fig. 2 Potential strain measurement locations

Results

The application of the former procedure leads to the selection of 10 strain measurements which are depicted in Fig. 3. Two of them are strain gauges in the bolts and 8 more on both flange rings measuring the strains in tangential direction.

The result of all 120 test cases is of satisfying accuracy. The test case with the worst approximation is given in Fig. 4. The red color indicates areas of critical gapping. The reconstructed gap distribution is quite similar as the reference. In summary it can be stated that the gap distribution can be reconstructed based on a few (= 10) strain measurements.

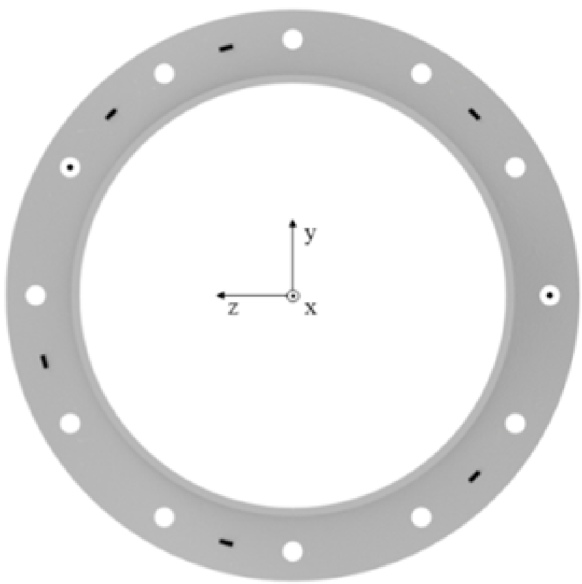

Fig. 3 Selected strain measurements

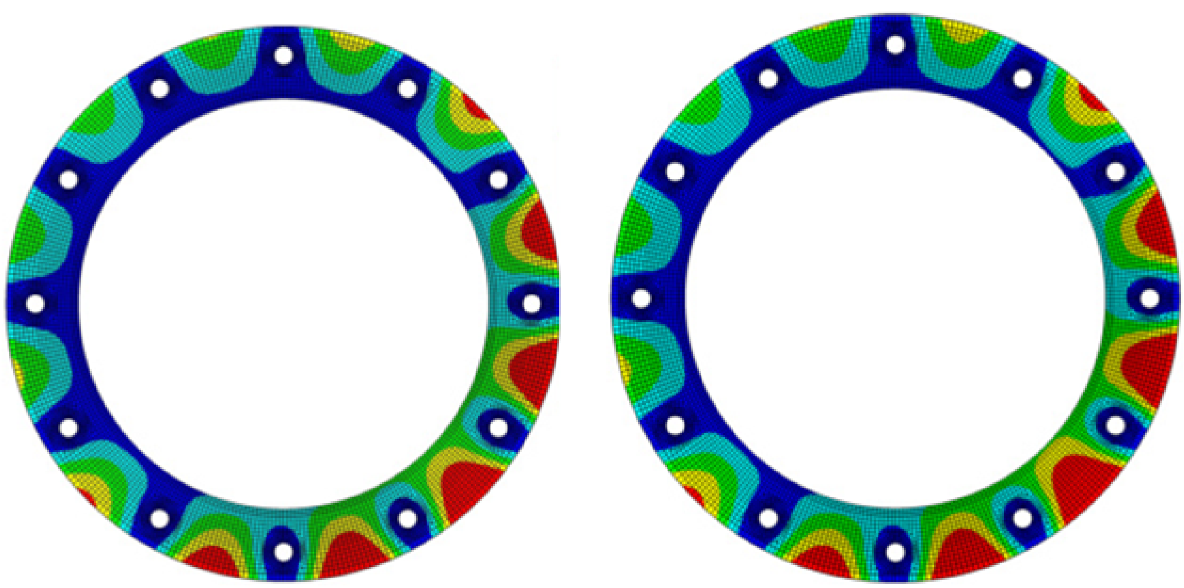

Fig. 4 Strain based gap (right) vs. reference computation (left). The red color indicates a critical opening in the contact area

Comments on the Measurability of the Strains

An important criterion for feasibility is the magnitude of the strains that occur. Very small strains do not lead to any problems in the simulation but are not measurable with real sensors. A look on the strain data reveals that in case of critical loads (like Fig. 4), the strains are in a good measurable range. This is not necessarily the case for low loads, but the flange is then not in a critical state.

Comments on the Sensitivity to Noisy Data

To get a first impression of the sensitivity to noise, the strains were artificially polluted by random numbers. It turns out that test sets with critical loads react very robustly to noise.

Comments on the Real-Time Capability

Real-time capability requires that in an actual realization, the transformation of the strain measurements into the gap distribution by the matrix-vector multiplication (7) is faster than the sampling time of the data acquisition system. Corresponding investigations have shown that this takes less than one millisecond with 10 sensors and almost 8000 entries in the gap vector $\mathbf{g}$.

Conclusion

The numerical investigation presented suggests that the gap distribution inside a flange contact can be reconstructed via a model based virtual sensor with few strain measurements. This could be used to assess the tightness, for example. It turns out that the result has a certain robustness against noise and the strains are in a range that is good to measure, at least for critical load situations. The arithmetic operation that converts the strains into the gap distribution takes less than a millisecond.

The reconstruction of the gap distribution presented here is actually a kind of worst case in terms of effort. Simpler questions such as ‘Is the gap uncritical or not?’ would probably be more relevant. It is conceivable, for example, to train a neural network for this question without reconstructing the entire gap distribution.

References

1. Witteveen, W., Kuts, M., Koller, L., 2023, “Can transient simulation efficiently reproduce well known nonlinear effects of jointed structures?”, Mechanical Systems and Signal Processing, 190, doi:10.1016/j.ymssp.2023.110111.
2. Dreher, T., Brake, M., R., W., Seeger, B., Krack, M., 2021, “In situ, real-time measurements of contact pressure internal to jointed interfaces during dynamic excitation of an assembled structure”, Mechanical Systems and Signal Processing, 160, doi:10.1016/j.ymssp.2021.107859.
3. Witteveen, W., Desch, S., Koller, L., “Can real-time flange tightness monitoring be possible with strains? A numerical pre-study.”, Journal of Structural Dynamics [En ligne], Special issue on Tribomechadynamics, under review
4. Pichler, F., Witteveen, W., Fischer, P., 2017, “A complete strategy for efficient and accurate multibody dynamics of flexible structures with large lap joints considering contact and friction”, Multibody System Dynamics, 40(4):407–436, doi:10.1007/s11044-016-9555-2.370
5. Chatterjee, A., “An introduction to the proper orthogonal decomposition”, SIAM Journal on Scientific Computing, 78(7):808–817, URL http://www.jstor.org/stable/24103957.
6. Chaturantabut, S., Sorensen. D., C., 2010, “Nonlinear model reduction via discrete empirical interpolation”, SIAM Journal on Scientific Computing, 32(5):2737–2764, doi:10.1137/090766498.