THE INFLUENCE OF TIGHTENING TORQUE ON MODAL PARAMETERS OF STRUCTURES WITH BOLTED JOINTS

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Resumo. *O monitoramento do torque de aperto ainda é caro, feito com medidas diretas e não automatizado. Encontrar características vibracionais que sejam capazes de prever as perdas no torque de aperto ainda é um desafio, devido à complexidade dos efeitos não lineares e às incertezas relacionadas às juntas parafusadas. Desta forma, este trabalho pretende investigar a capacidade de detectar variações no torque de aperto e classificar se a estrutura está em condição segura simplesmente analisando parâmetros modais para diferentes torques. Para isso, foram realizados experimentos a uma entrada aleatória em uma viga de duas partes conectada por uma junta parafusada ligada a um excitador para extração de frequências de ressonância e razões de amortecimento. A análise foi feita utilizando a Distância Quadrada de Mahalanobis treinada com os conjuntos de características no estado sem dano (torque seguro). Apesar da dificuldade de lidar com a variabilidade gerada pelas remontagens, a baixa taxa de falsos negativos quando elas são desconsideradas indica que estes parâmetros modais podem ser usados como indicadores de danos relacionadas a variações de torque de aperto menores do que as encontradas atualmente na literatura.*

Keywords: *Juntas Parafusadas, Monitoramento de Torque, Detecção de Danos, Distância Quadrada de Mahalonobis*

Abstract. *Tightening torque monitoring is still expensive, with direct measures and principally not automatized. Verifying tightening torque from indirect vibration measures through structural health monitoring techniques instead of employing manual torque wrenches is of great technological interest. Nevertheless, finding sensitive vibration features that can predict tightening torque losses is still challenging due to the complexity of nonlinear effects and uncertainties related to bolted joints. Thus, this paper intends to investigate the capacity of detecting variations in tightening torque and classify if the structure is in a safe torque condition only by analyzing modal parameters for different torques. For this, experimental tests were performed to a white noise input on a two-part beam connected by a bolted joint attached to a shaker to extract resonance frequencies and damping ratios. The analysis was done using the Mahalanobis Squared Distance between the clusters of features in a healthy state of reference to the damaged ones. Despite the difficulty of dealing with the reassemblies' variability, the low false-negative rate when they are disregarded indicates that these modal parameters can be used as damage features related to variations of tightening torques smaller than those currently found in the literature.*

Keywords: *Bolted Joints, Torque Monitoring, Damage Detection, Mahalonobis Squared Distance*

1. INTRODUCTION

Bolted joints are one of the principal forms to attach components of assembled mechanical systems, ensuring their structural stability and proper functioning. Thus, they must always be in a sufficiently healthy condition to provide safe operation. Thereby, periodic maintenance is required; economically speaking, bolted joints maintenance can become expensive, not only due to the costs of structural collapse or failure but due to maintenance stops, crew mobilization, and field operating costs. In this context, detecting the variation of the tightening torque during the operation of equipment through indirect vibration measures is of great interest for developing safer, faster, and cheaper structural health monitoring methods, as proposed in Chevallier *et al.* (2019). However, this is still a technological challenge because of complex nonlinear effects due to frictional interactions on the connection interface, such as hysteretic behavior. Furthermore, there is much uncertainty related to environmental and operational variations.

The literature still needs to investigate what parameters can indicate damaged conditions for decision-making on the joints' tightening torque level. These metrics should be of easy extraction and analyzed through feature classifiers sensitive to the tightening torque variation, in addition to being preferably extracted from cheap and standard tools already used on the monitoring of these structures. Consequently to the experimental requirements, this work aimed to identify and connect the features extracted from the Transmissibility Functions: the damping ratio and the resonance frequency from the 6-th vibration mode; the damage classification was made from the Mahalanobis squared distance (MSD) between the clusters of a graph correlating the features. The outline of this work is organized as follows: first, in Section 2.the whole procedure proposed for damage detection is explained, including the feature extraction and calculating the damage index. Then, in Section 3., it is described the experimental setup used to illustrate the proposed methodology. The results and discussion of the damage detection on this structure are presented next in Section 4. Moreover, finally, in Section 5., some final remarks about the work are presented.

2. DAMAGE DETECTION

The methodology proposed to damage detection in bolted joints takes modal parameters as sensitive features and is illustrated in Fig. 1.

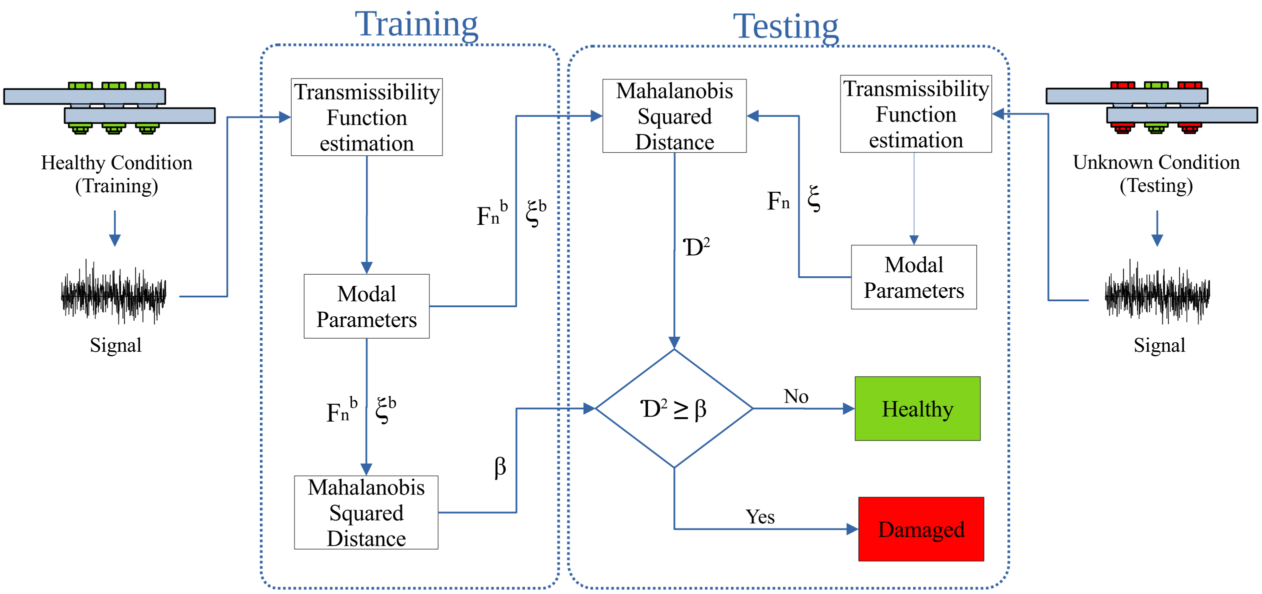


Figure 1. Flowchart of the damage detection algorithm

First, from the time response to a single-input and single-output (SISO) white noise test for different torque conditions, it was possible to estimate the transmissibility function and observe the vibration modes that are more sensitive to torque variations. Then, modal parameter identification is made for this mode through the Complex Exponential (CE) method, exemplified by Lieven *et al.* (2001), that extracts the resonance frequency (F_n) and the damping ratio (ξ). A damage index ($\mathcal{D}^2$) is calculated by the MSD between the training matrix $\mathbf{X} = [{F_n}^b \quad \boldsymbol{\xi}^{\boldsymbol{b}}]$ obtained from the features to a baseline condition in a healthy state and the testing matrix $\mathbf{Z} = [F_n \quad \boldsymbol{\xi}]$ under supposedly unknown torque conditions:

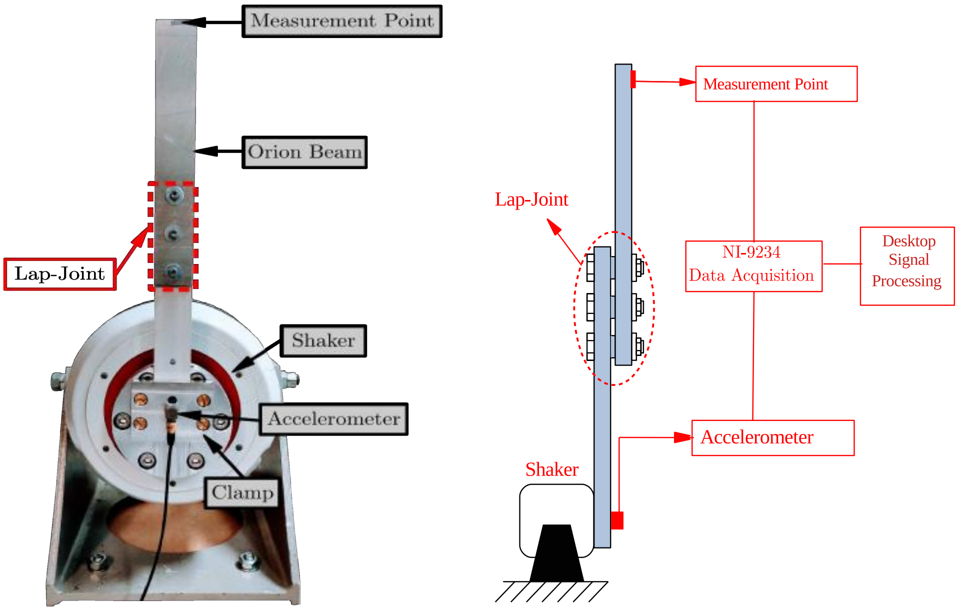
$$\mathcal{D}^2 = (\mathbf{Z} - \boldsymbol{\mu})\,\boldsymbol{\Sigma}^{-1}\,(\mathbf{Z} - \mu)^T \tag{1}$$

where $\mathcal{D}^2$ is the MSD, μ is the mean vector of the training data, $\boldsymbol{\Sigma}$ is the covariance matrix of the training data set.

A threshold is also defined as the highest $\mathcal{D}^2$ value when considering the training data to be both the training condition and the unknown test condition on Eq. 1. Therefore, every $\mathcal{D}^2$ value greater than this threshold is identified as a damaged torque condition.

3. EXPERIMENTAL SETUP

Figure 2 shows the experimental setup, named as Orion beam by Teloli *et al.* (2020). It consists of a duraluminium beam assembled with two parts connected by three M5 bolts in a bolted joint with controlled tightening torque, measured with a torque wrench. The structure is vertically attached to a shaker on the lower end. To measure the outputs, an accelerometer and a laser vibrometer at the upper end are utilized. The excitation used was a white noise with an RMS base acceleration level of 4 $\mathrm{m/s^2}$ and the frequency bandwidth of 10 Hz to 2000 Hz. The white noise input is chosen here because it is a broadband input, and therefore allows the analysis of all the modes of vibration within the frequency range. Besides that, this kind of input is also the most common in industrial operations.



(a) Assembled setup (b) Schematic diagram

Figure 2. Experimental setup - Orion beam.

For all the experiments, the central bolt of the connection has a fixed tightening torque of 80 cNm, and the other two have different controlled torque conditions that determine the health state of the structure. Therefore, it is essential to highlight that every torque variations mentioned throughout this work refer only to these two bolts. These positions have also been illustrated previously in the flowchart of Fig. 1 for better knowing. Thereby, the tests were performed to 5 different torque conditions: 80 cNm, that is considered as the healthy state (H); 60 cNm, that is the first level of damage considered (D1); and respectively 30 cNm (D2); 20 cNm (D3) and 10 cNm (D4). For each condition, it was performed six measures, and then this set of experiments was repeated for three different reassemblies of the joint, totalizing 90 tests.

4. RESULTS AND DISCUSSION

Analyzing the estimated transmissibility function for all the experiments, one can recognize the structure's behavior due to tightening torque and assembly variations, which is shown in fig. 3. A previous analysis provides that the 6-th modes of vibration is more susceptible to the tightening torque fluctuations. The modal parameters of the 6-th mode of vibration, i.e., the resonance frequencies F_n and damping ratios ξ were estimated through the Complex Exponential (CE) method, exemplified by Lieven *et al.* (2001).

Figure 4 exposes the transmissibility on the 6-th mode frequency range of the more beneficial observability. The line style changing and color-changing represent respectively reassemblies and torque conditions. As Fig. 4(a) shows three different reassemblies, it is difficult to identify the effects of variation separately on the system response that are due to torque variations, which is more evident in Fig. 4(b). These features is shown in fig.5 using a boxplot.

The features representation as individual observations does not quite represent the damage, in order to check if a feature set observation is more precise, a F_n x ξ plot is presented in figure 6.

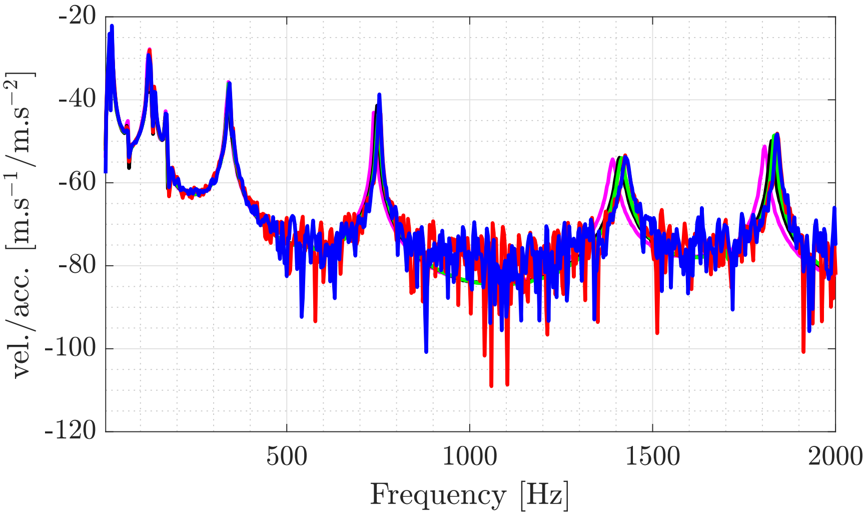
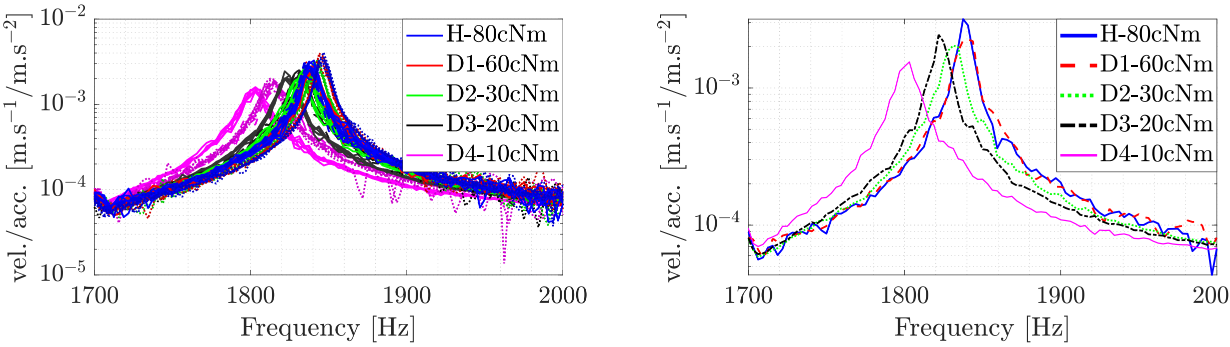


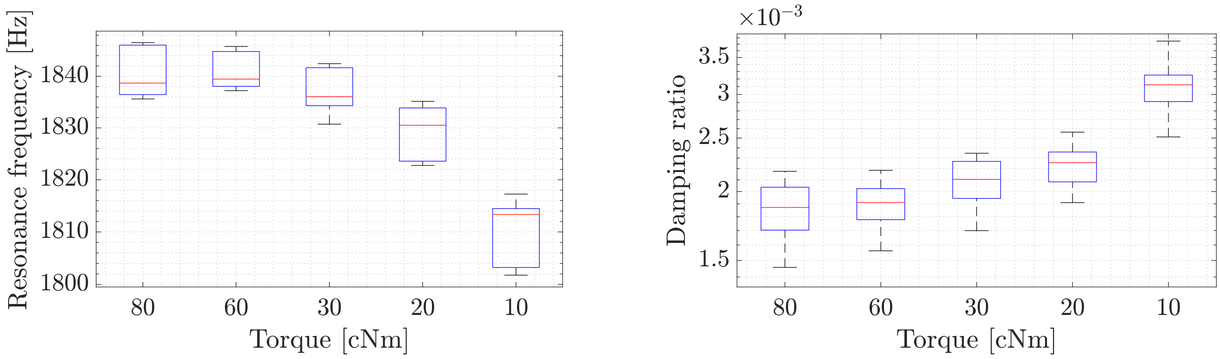
Figure 3. Transmissibility function for individual signals of the five tightening torques



(a) All torques, repetitions and assemblies.

(b) First repetition of a single assembly for each torque.

Figure 4. Transmissibility on the frequency range of the 6-th vibration mode



(a) Resonance frequency boxplot.

(b) Damping ratio boxplot.

Figure 5. Boxplots of the features of the 6-th mode.

Figure 6 shows some overlapping between the clusters from different torque conditions; at the same time, some clusters are separated in distant regions of the plane that represent realizations of the same torque is apparent in the case of 10 cNm. This situation can be explained by 3 different assemblies of data in Fig. 6. The reassembling procedure is one of the primary sources of uncertainty in bolted structures, due to some changes in the structure geometry when the components are positioned, besides possible variability on the pressure distribution on the contact surface as mentioned in Teloli *et al.* (2020). This fact also justifies the design of the Orion beam's lap joints, which have central contact patches around the bolt holes to decrease these uncertainties.

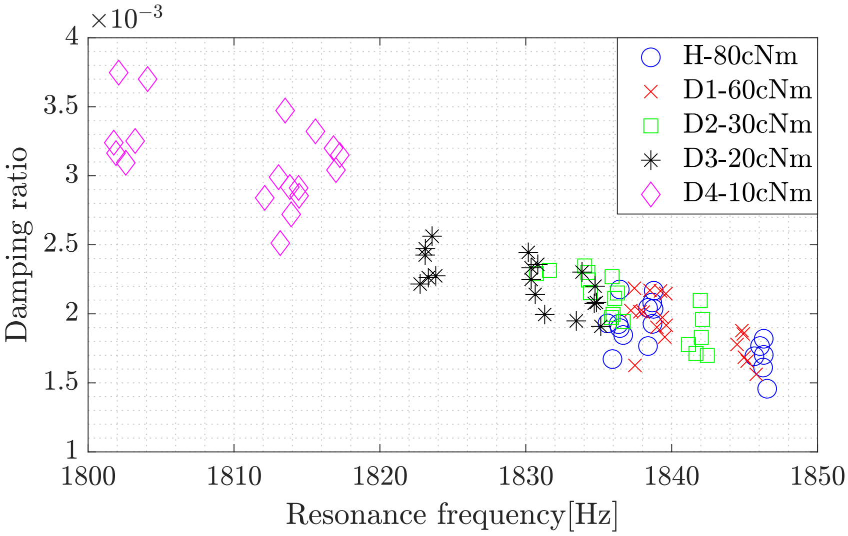


Figure 6. Features F_n x ξ plot

However, they are still present and manifesting themselves as changes in the modal parameters. The overlapping is not ideal for SHM applications because it mischaracterizes the system's different conditions, requiring more robust classifiers that are still a challenge not fully explored in the literature. Despite the overlapping problem, it could be possible to classify damaged conditions with the machine learning procedure described in Section 2. In this case, it is randomly selected half of the healthy condition (80 cNm) feature data to be used as training data, leaving the other half as testing data to verify if the methodology can identify an unknown condition healthy reliably. Then, employing the MSD between all the testing data (that includes the second half of healthy data and all the damaged ones in ascending order of severity) to the training healthy condition cluster, it is possible to compute a damage index $\mathcal{D}^2$. Figure 7 illustrates the calculated damage index for all the experimental tests. It is also presented the threshold β, that tries to classify in a binary way the health condition as healthy or damaged with a straight line tangent to the training point with the higher $\mathcal{D}^2$.

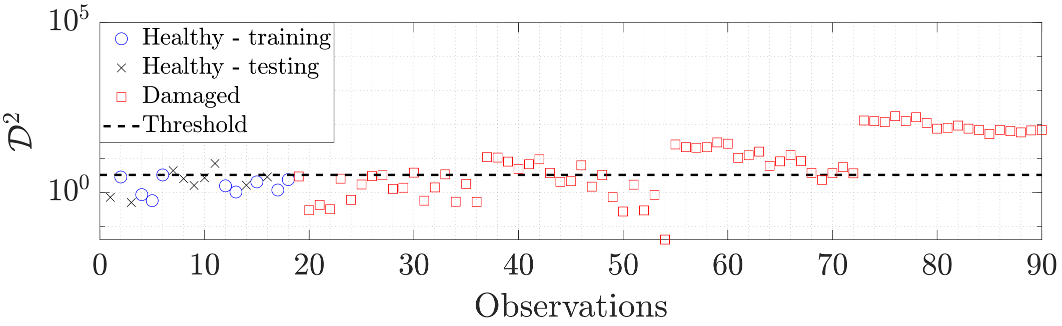


Figure 7. Binary damage classifier for all reassemblies

Figure 7 shows that the binary classification using Mahalanobis squared distance is not precise and classifies many damaged conditions as healthy and healthy conditions as damaged. As discussed before, a potential problem is the difficulty of classical classifiers to deal with the reassembling uncertainties. So, it was considered only the first assembly to evaluate the modal parameters' capability on identifying the loosening of the tightening torque at least after a single assembly. After separating the first assembly data, 50 synthetic pairs of features were added for each condition. These synthetic parts were generated randomly following gamma distributions with α and β parameters extracted from each feature cluster torque condition to overcome the lack of more experimental realizations. Figure 8 illustrates the new clusters of features estimated.

Figure 8 proved that the new features are far more defined in different clusters with a better statistical variability due to a large number of realizations. They were indicating that it would be more obvious to detect the presence of damage. Thus, the same procedure of the MSD between the training data defined again as half of the undamaged tests and the remaining testing data. Figure 9 shows the $\mathcal{D}^2$ for this scenario.

Figure 9 proves that the new damage classifier is more accurate by analyzing the type I error and type II

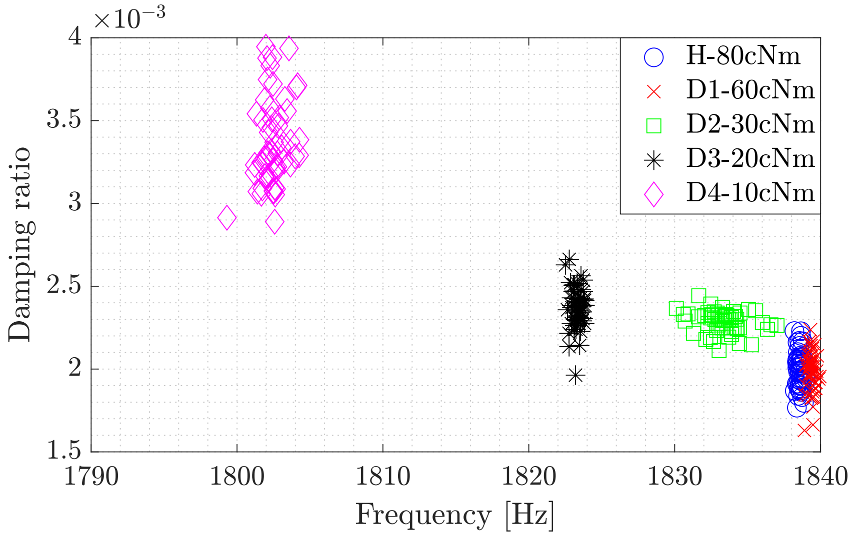


Figure 8. Features $F_n \times \xi$ plot for a single assembly with the synthetic data

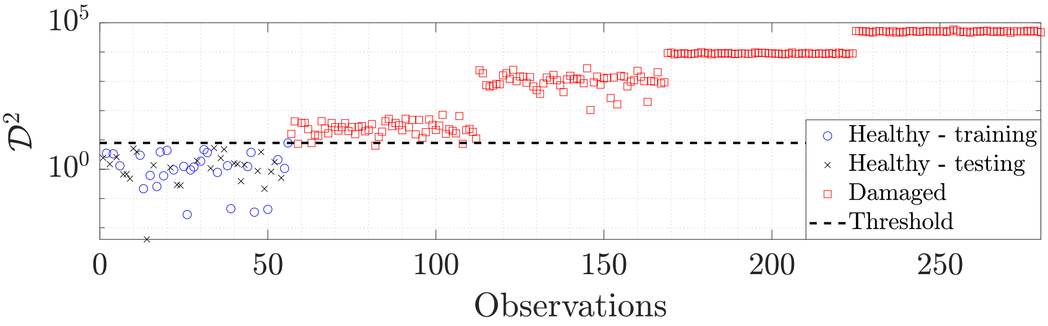


Figure 9. Binary classification for a single assembly with synthetic data

error. Another way to see the effectiveness of separating assembles is a Receiver Operating Characteristic graph (ROC), seen in Fig. 10. It should show the higher chance of obtaining false positives without separation of assembles and less chance with the separation.

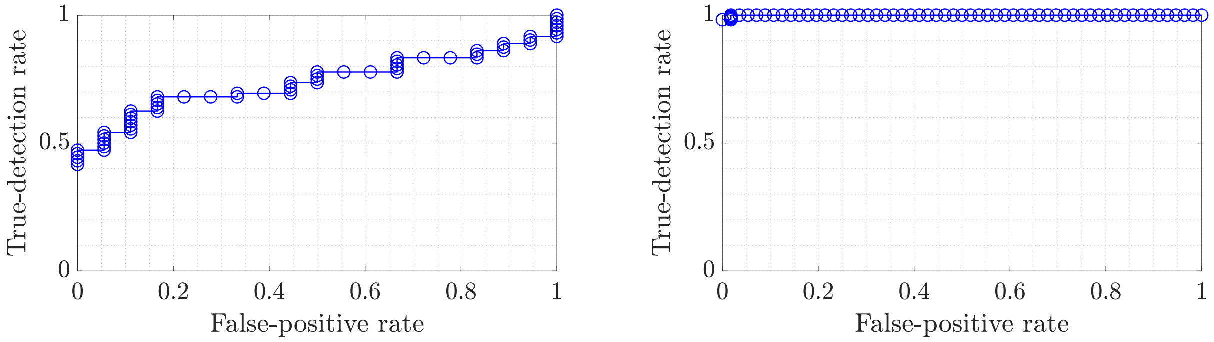
Table 1. Types I and II errors for the two binary classifiers

	Type I error	**Type II error**
All assemblies	28.5714%	60%
First assembly plus synthetic data	0%	1.8182%

Figure 10(b) represents the classification without reassemblies where one can see is more precise on correct detection rate compared to false positive rate than Fig. 10(a). This means that statistically speaking, separating assembles provides more reliable results. The proposed methodology is quite sensitive compared to other recent works in the literature such as Luo and Yu (2017), in which only damage detection for torque losses of 87.5% of initial torque (20 Nm to 2.5 Nm) is reported. Here, with the proposed method is possible to detect damages with losses of only 25% (80 cNm to 60 cNm).

5. FINAL REMARKS

Despite the beam vibration's nonlinear behavior, strongly related to the bolts' tightening torque, linear modal parameters were responsively suitable to the tightening torque's structural variation. Still, the uncertainty on the beam response related to the reassembly limited the classifier accuracy to a single assembly and therefore requires a more robust classifier in the future that can overcome these effects. Another feature of interest to



(a) ROC curve for all assemblies (b) ROC curve for a single assembly

Figure 10. Receiver Operating Characteristic plot

detect torque variation in future works could be the dissipated energy of hysteresis effect based on a Bouc-Wen oscillator, similar to the model proposed by Teloli *et al.* (2021), which would be able to take into account nonlinear effects. It is also important to note that the damage indices calculated in this paper have characteristic progressive values for each torque condition, which could be interpolated by some regression techniques such as Gaussian Process Regression. It could help identify whether the structure is healthy or damaged and quantify how damaged it is, which is now a future research goal.

It is also important to note that the damage indices calculated in this paper have specific progressive values for each torque condition, which could be interpolated by some regression techniques such as Gaussian Process Regression. It could help identify whether the structure is healthy or damaged and quantify how damaged it is, which is now a future research goal.

6. AKNOWLEDGEMENTS

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