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# Response phase mapping of nonlinear joint dynamics using continuous scanning LDV measurement method

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## Abstract

This study aims to present a novel work aimed at locating discrete nonlinearities in mechanical assemblies. The long term objective is to develop a new metric for detecting and locating nonlinearities using Scanning LDV systems (SLDV). This new metric will help to improve the modal updating, or validation, of mechanical assemblies presenting discrete and sparse nonlinearities. It is well established that SLDV systems can scan vibrating structures with high density of measurement points and produce highly defined Operational Deflection Shapes (ODSs). This paper will present some insights on how to use response phase mapping for locating nonlinearities of a bolted flange. This type of structure presents two types of nonlinearities, which are geometrical and frictional joints. The interest is focussed on the frictional joints and, therefore, the ability to locate which joints are responsible for nonlinearity is seen highly valuable for the model validation activities.

**Keywords:** ODS, nonlinearities, phase mapping, SLDV.

## 1. INTRODUCTION

This paper focuses on nonlinear structural dynamics of mechanical assemblies. The long term objective is to develop new experimental methods for the identification of nonlinearities. The model updating (or validation) is well established for mechanical systems under linear response conditions. However, as soon as the amplitude of vibration is increased linear validation methods break because of nonlinear responses [1]. There is a vast community of researches who are busy with characterization and quantification of nonlinearities [2]. However, one of the shortfalls in the nonlinear structural dynamics is the location of nonlinearities, especially when they are discrete and sparse. The lack of experimental methods for locating nonlinearities affects downstream the model updating process. In fact, it is difficult to know which finite element(s) of the model requires a better definition of its physics. Mechanical assemblies can present such a complicated scenario where individual monolithic components can be correctly updated but the validation of the assembly might face serious challenges. The major constrains being the contact interfaces which generate nonlinearity. Recently, the Reverse Path Method [3], [4] has been used for both locate and characterize the nonlinearities. This experimental method is based on random noise signal and the use of the multiple coherence function for locating nonlinearities. The major shortfall is to correctly locate the acquisition sensors (mainly contact sensors) in order to capture any loss of coherence caused by nonlinearity. Unfortunately, the test planning is not that easy when a limited number of sensors must used and neither practical if a test structure must be covered with far too many sensors. However, when sensors and excitation source are correctly planned the location of nonlinearity is well detected. This context triggered the use of a SLDV system to integrate the arduous challenge of locating nonlinearities. The major advantage of this contactless sensor is to generate highly defined ODSs either by stepping the laser beam over a dense measurement grid or by continuously scanning the beam over an area or a line [5]. The amplitudes of

the ODSs are often analyzed, since the amplitude of vibration matters. However, the observation of the ODS phase might be also helpful for detecting nonlinearities. This paper will present some results of a research focussed on the use of response phase mapping for location of nonlinearities.

## 2. TEST STRUCTURE AND MEASUREMENT SETUP

The test structure adopted for this study is a simple bolted flange as shown in Figure 1. It is made of two parts, the casings of which are different thickness, with two flanges bolted by 8 (M6) bolts. A Finite Element model was generated using the material properties presented in the Table 1.

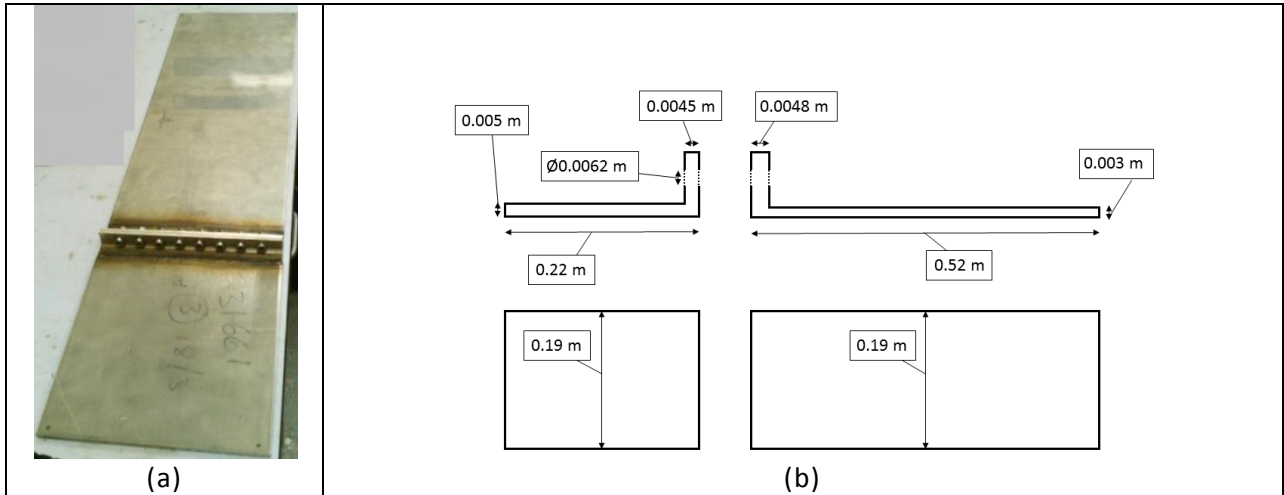


Figure 1 (a) Test structure and (b) CAD drawings

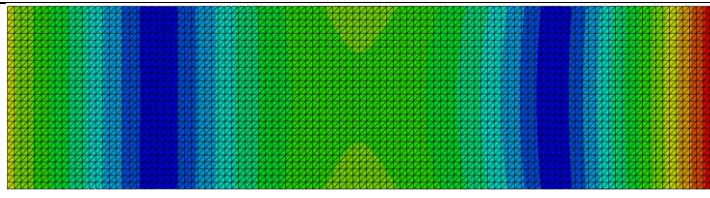
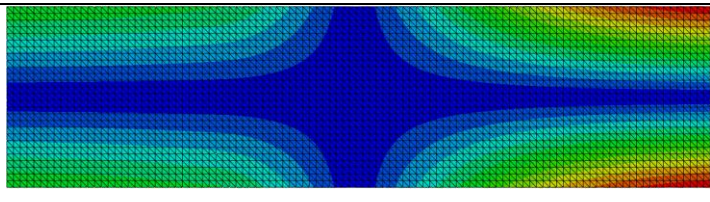
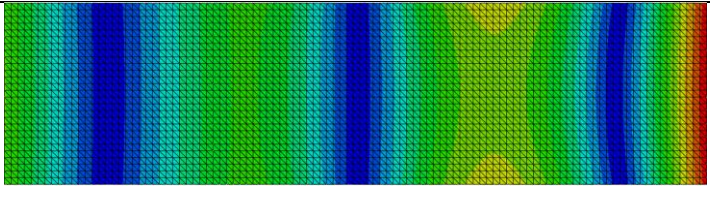
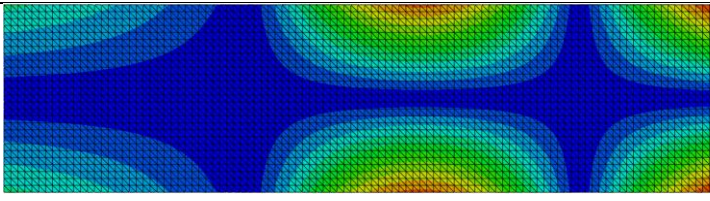
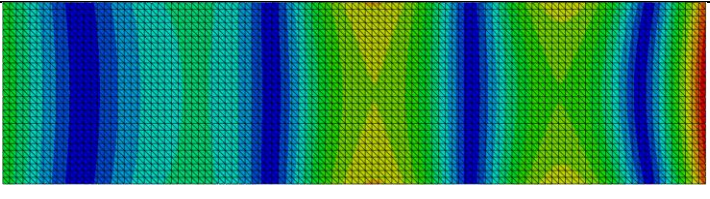
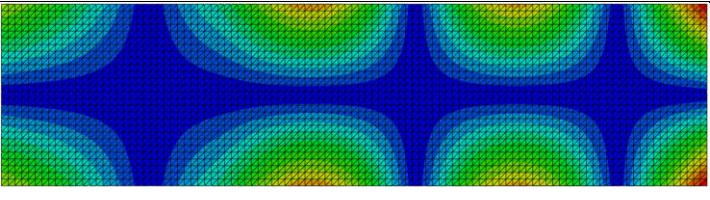
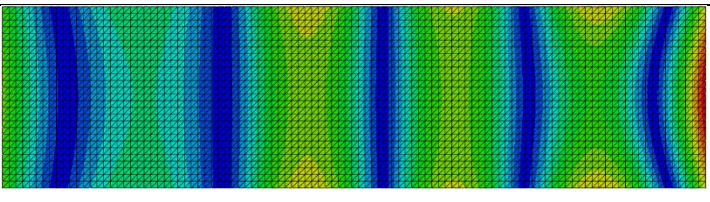
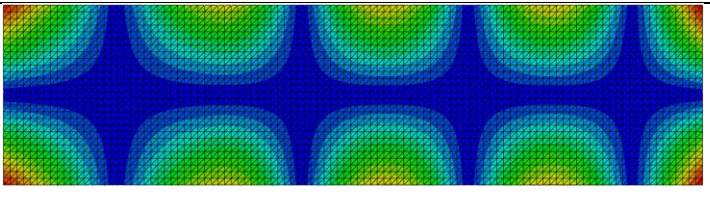
Variable	Symbol	Value
Young's Modulus	E	200 GPa
Poisson's Ratio	$\nu$	0.3
Density	$\rho$	7500 kg/m <sup>3</sup>

Table 1 Material properties

The structure has been studied following the boundary conditions applied during the experiment – free-free conditions. For this model, the plates are drawn in two separated parts using a 3D, solid, extrusion model. The nodes are merged in the assembly tab, after meshing separately both parts, using the ‘merge instances’ option. Moreover, the element type chosen is Tri C3D10 (0.007 m of size). No boundary condition is applied. The two meshed plates are represented in Figure 2. One can see that the holes in which the bolts are placed have also been modelled but not the bolts. The ten first modes are represented in Table 2 with the modal deflection shape and the values of the natural frequencies.



Figure 2 FE model

Mode	Frequency [Hz]	Modal Deflection Shape	Mode Type
1	27.822		B1
2	67.217		T1
3	82.880		B2
4	167.65		T2
5	177.25		B3
6	279.76		T3
7	306.33		B4
8	362.74		T4



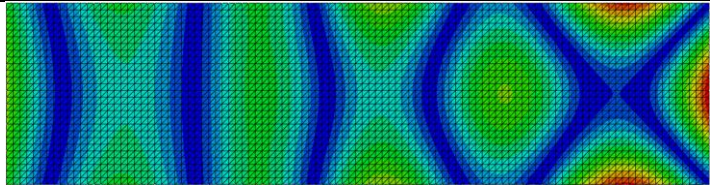
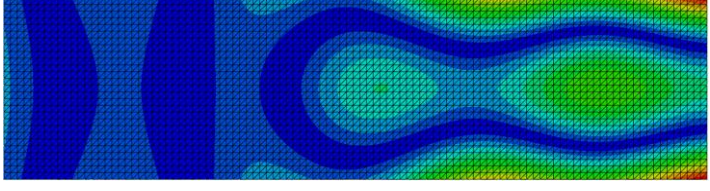
9	436.88		B5
10	466.58		N/A

Table 2 Natural Frequencies and mode shapes

The experimental and theoretical natural frequencies were correlated and presented in Figure 3. Modal analysis was carried out in linear regime. The discrepancy between the theoretical and experimental can be due to several minor factors, like the suspension of the specimen.

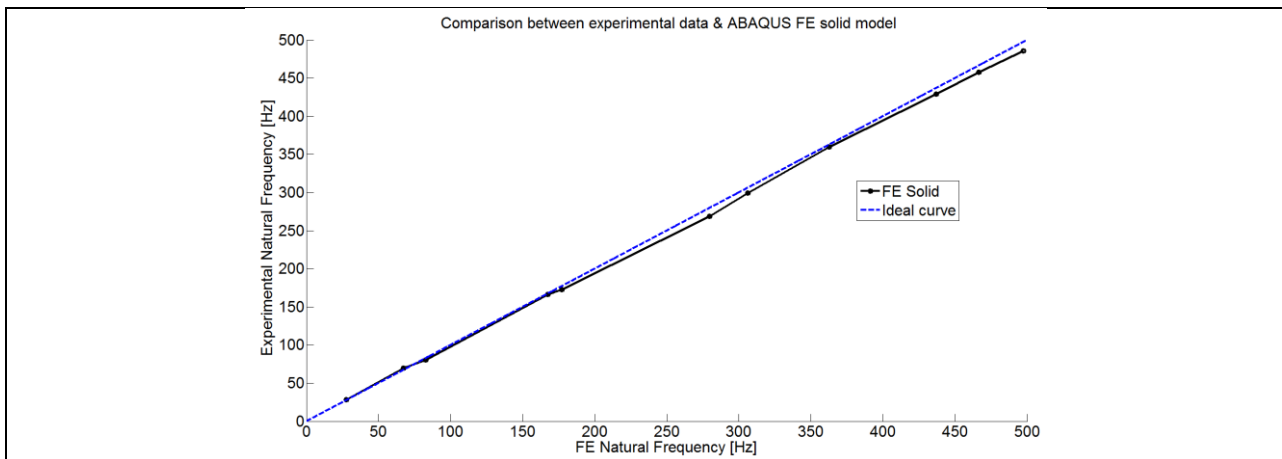


Figure 3 Correlation between experimental and theoretical natural frequencies.

The is suspended by a couple of strings and a turnbuckle so as to adjust its height with respect to the shaker position, as shown in Figure 4(a). The structure is excited by a shaker attached by a stinger to force sensor glues to the structure. The output force signal is produced by the computer interface which is transmitted to the shaker through a signal amplifier. Figure 4 (b) shows the measurement setup and the laser signal level, which is an acceptable signal quality. Figure 5 shows the schematic of the measurement chain including the control panel, which performed the ODS measurements.

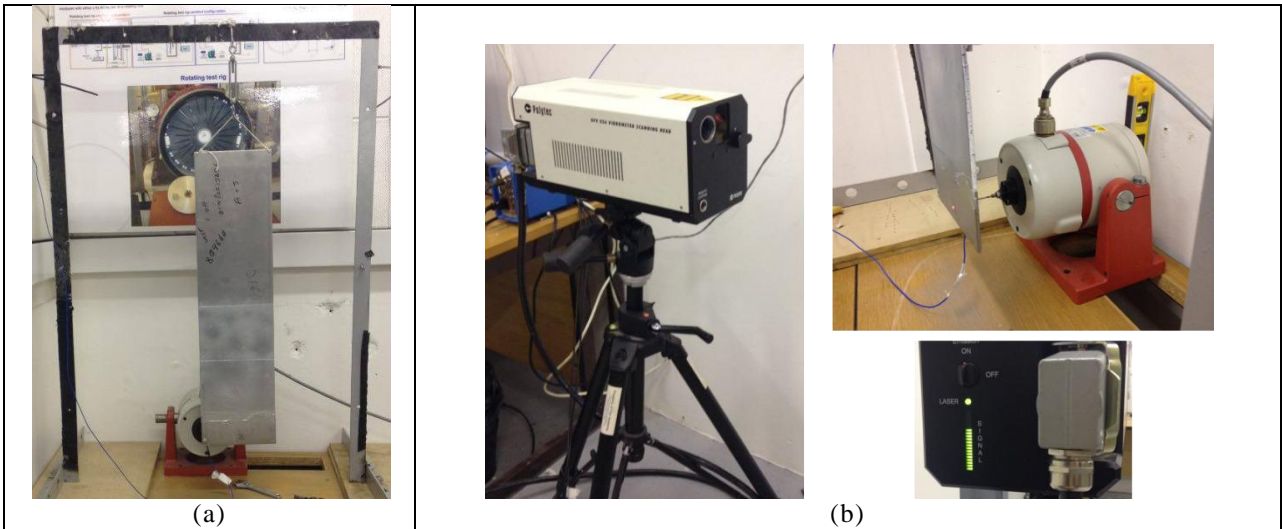


Figure 4 Measurement setup

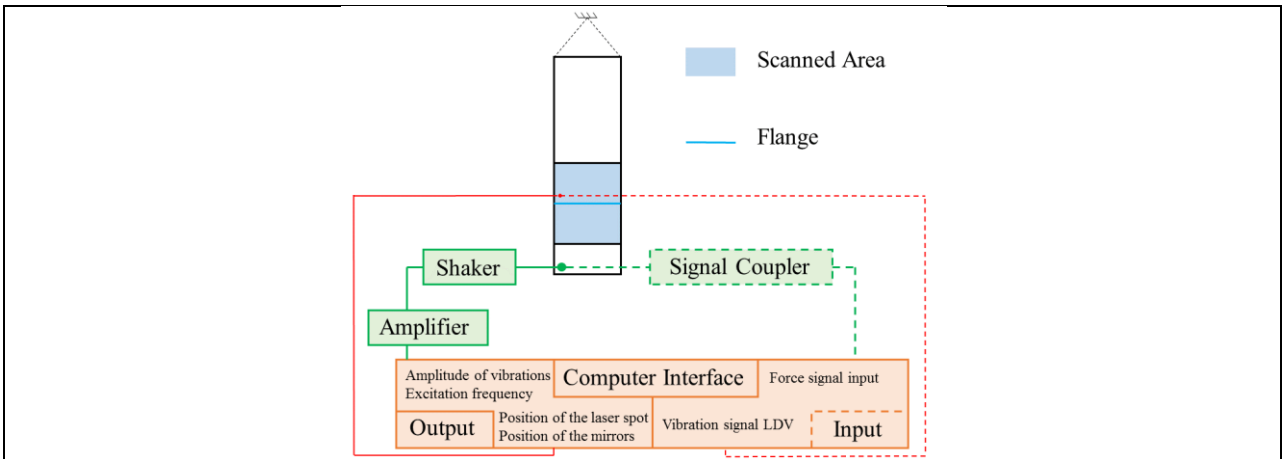


Figure 5 Schematic of the measurement chain

### 3. DESIGN OF EXPERIMENT

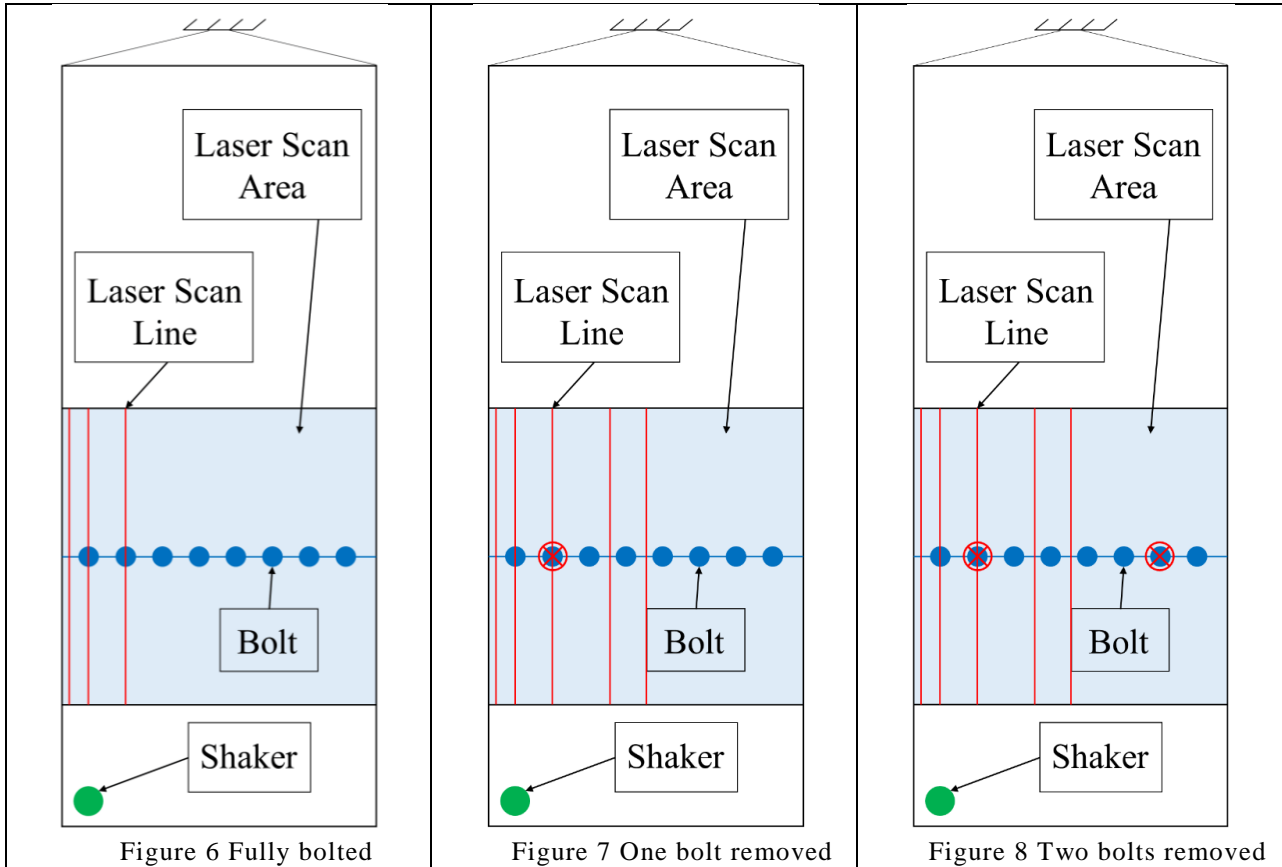
The design of the experiment was developed upon some experimental results obtained from an earlier research work produced by the author [ ] on the same test structure. This study was focussed on the development of a strategy for nonlinear detection based on strain analysis. This aimed at ranking the most sensitive natural frequencies to nonlinearities and the outcome from that research is presented in Table 3. So, the same natural frequencies were selected for these experimental measurements.

Ranking	Mode Number	Frequency [Hz]	Mode type
1	8	360.5	T4
2	4	166.5	T2
3	6	269	T3
4	2	69.5	T1

Table 3 Selection of mode shapes for nonlinear identification

The experiments are executed by referencing the output voltage to the amplifier which was kept at fixed gain value and this is checked prior any experiment. So, the amplitude of vibration is referenced thanks to the amplitude monitoring *LABVIEW* control panel. This program allows to visualise the force

signal and peak-to-peak amplitude in Newton for one given excitation frequency and one given amplitude of vibration. Therefore, it makes it possible to adjust the amplifier gain so that the force stays the same at one given frequency and one given excitation level for every new measurement. One reference frequency is chosen – 200Hz – and one vibration amplitude level 0.4V. At 200Hz, for an amplitude level of 0.4V, the force signal peak-to-peak gives a value of 12.3N. The amplifier gain is therefore adjusted for every new measurement to match this value at this given frequency and this amplitude level. For each frequency, the structure is then excited at five increasing levels of vibration: 0.4V, 0.5V, 0.6V, 0.7V & 0.8V. First, for each frequency and each level of vibration a Straight Line Scans are executed following the pattern shown in Figure 6, Figure 7 and Figure 8.

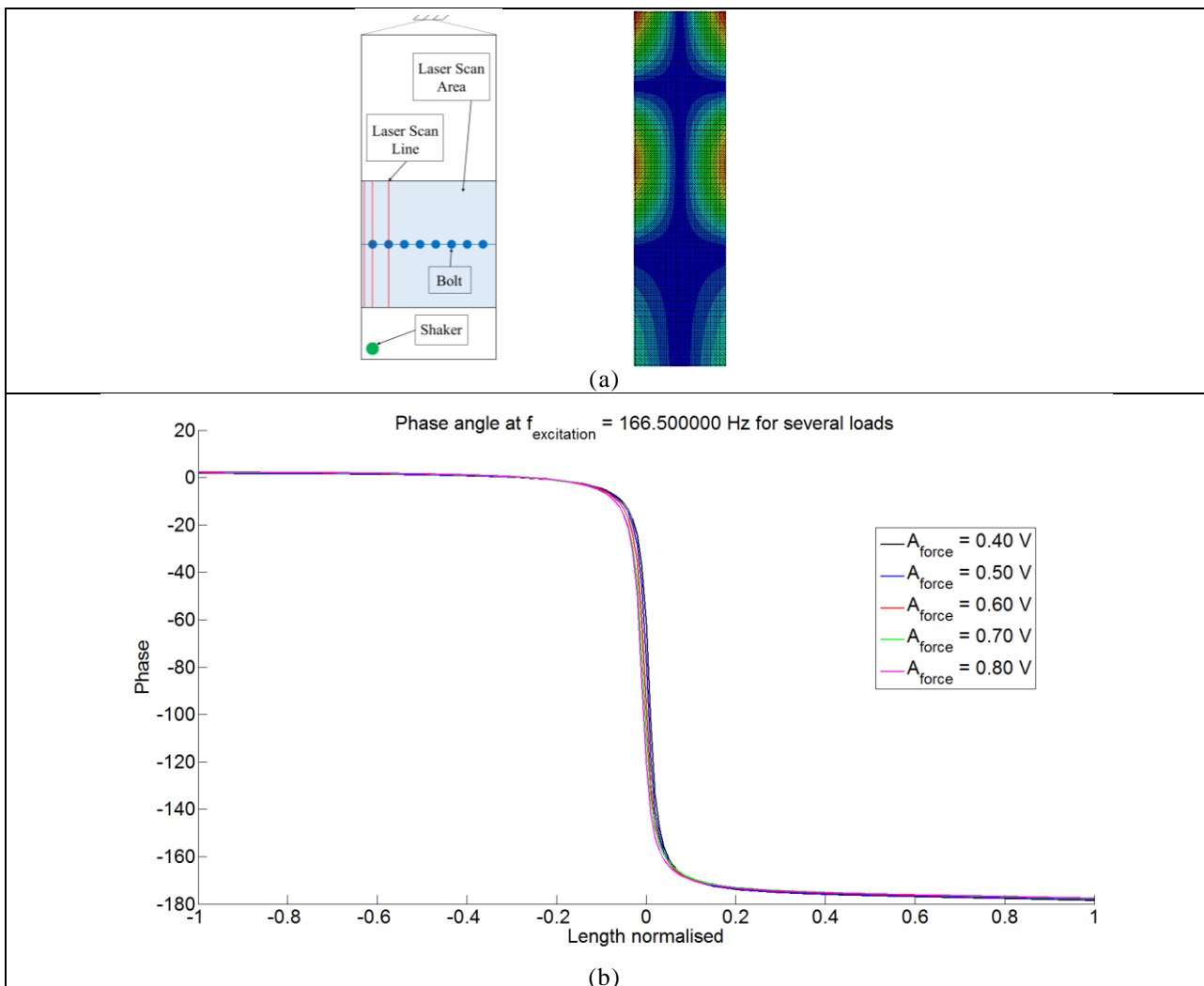


Straight lines are chosen to be scanned for each frequency at each level of vibration. The magnitude and phase angle are computed in the *LABVIEW* program and saved in *EXCEL* Files. For all experiments the signal is acquired for 15 seconds at a rate of 5000 samples per second. The response signal is referenced according to the Y-mirror signal so that all measurements are recorded at the same starting point, when the Y-mirror signal crosses zero.

In order to analysis the effect of nonlinearities due to the bolted joint, measurements are carried out using different bolting configurations. Three lines are measured for the fully bolted structure as seen in Figure 6. One bolt is removed and five lines are measured across the flange as shown in Figure 7. Finally, an additional bolt is removed and still five lines are scanned across the flange as shown in Figure 8.

## 4. EXPERIMENTAL RESULTS

This section will report the experimental results obtained from test carried out for the mode shape 2T (166.5Hz- second torsional) and for the three bolting configurations adopted. The excitation frequency for all the experiments was kept fixed at the natural frequency for the underlying linear system (ULS), which is assumed to be at the lowest level of excitation force. This is justified by assuming that all nonlinearities are not activated for low level of vibrations. For higher amplitude levels of vibration the nonlinearities are activated and the max response frequency of the system will move away from the one of the ULS. The ODSs are always measured at the same excitation frequency for any level of excitation force. So, the phase of the ODSs will capture the time lag for the same point to reach the same vibration amplitude. Figure 9(a) shows on the left the sketch of the flange with the three line scans and on the right the mode shape under investigation. Figure 9(b) shows the overlap of the ODSs phase of the line scan, the first line from the left in Figure 9(a). Figure 9(c) shows the overlaps of ODSs phase of the line scan, the second line from the left in Figure 9(a). Finally, Figure 9(d) shows the overlaps of ODSs phase of the line scan, the third line from the left in Figure 9(a). One can immediately appreciate that the ODSs phase maps show a clear change caused by the increased excitation force. This happens across the bolted flange and where the torsional nodal lines layup. One can also appreciate that ODSs phase tend to open up the closer the scan line is to the centre of the flange. This shows that phase mapping can be revealing useful information about location of nonlinearity.





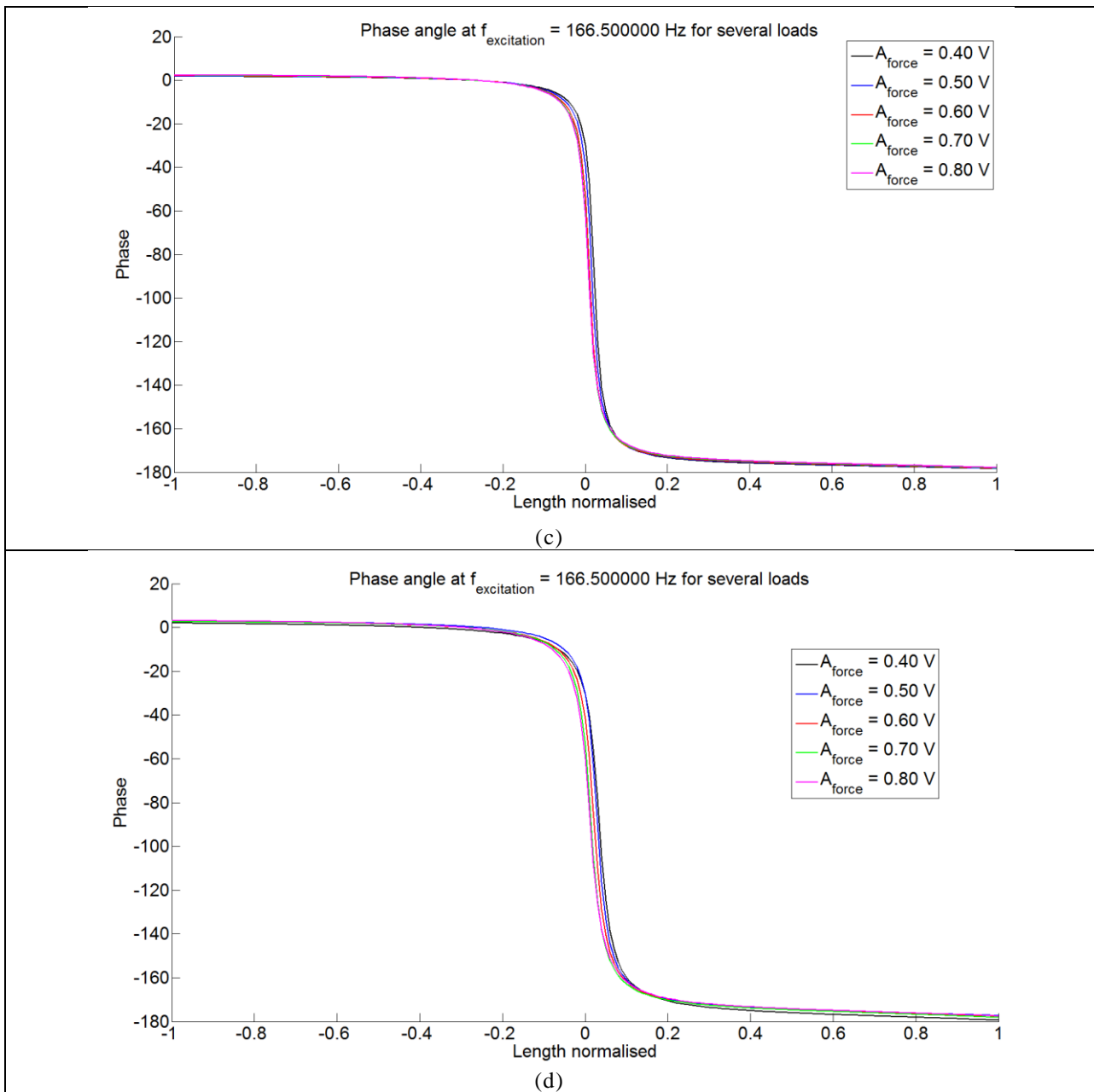
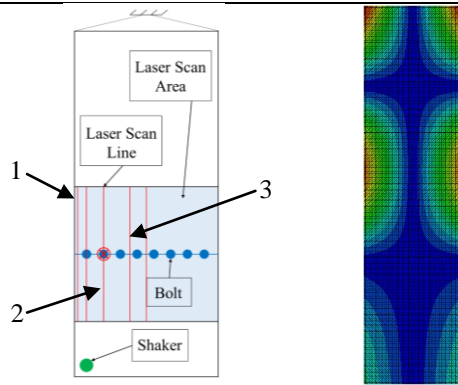
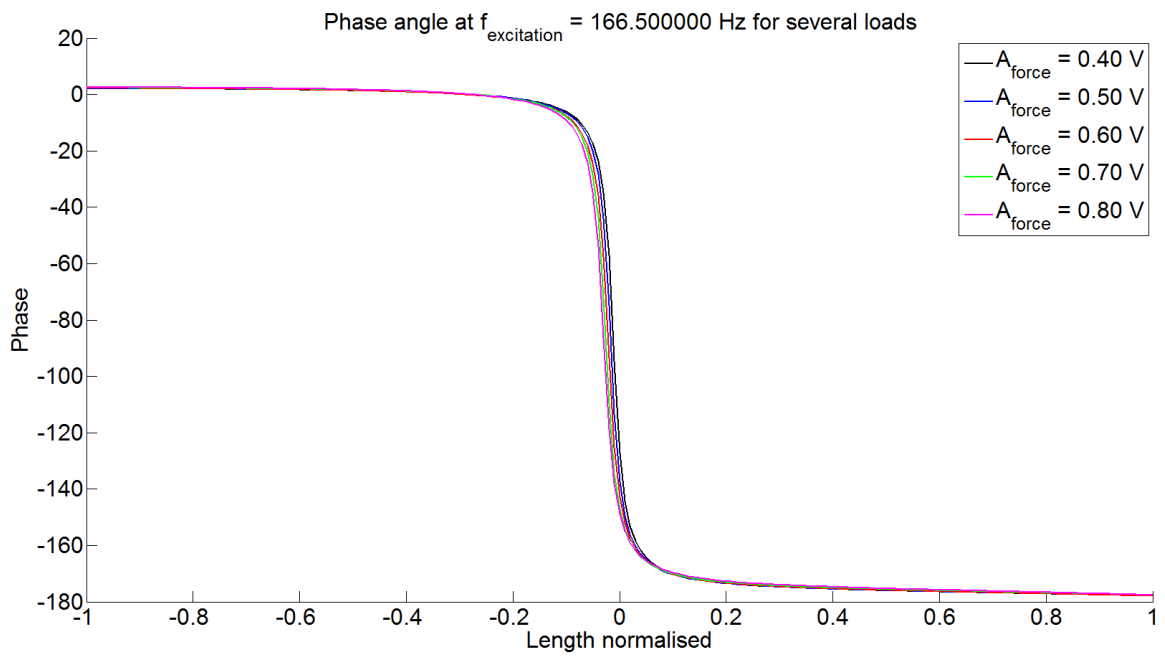


Figure 9 ODSs phase for straight line scans for fully bolted flange

The next attempt was to increase the level of nonlinearity by removing one bolt and repeat the same experiments but adding some extra scan lines. Figure 10(a) shows on the left hand side the sketch of the flange with the added extra scan lines. Figure 10(b) shows the ODSs phase for the scan line number 1. Figure 10(c) shows the ODSs phase for the scan line number 2 and, finally, Figure 10(d) shows the ODSs phase for scan line number 3. One can observe that the removing of one bolt makes the system to show more nonlinearity for the same given excitation forces. In fact, the first scan line shows different opening from the fully bolted to the one bolt remove case. However, the closer the line scans are to the middle torsional line the wider the opening of the ODS phase is, see Figure 10(d).



(a)



(b) scan line-1

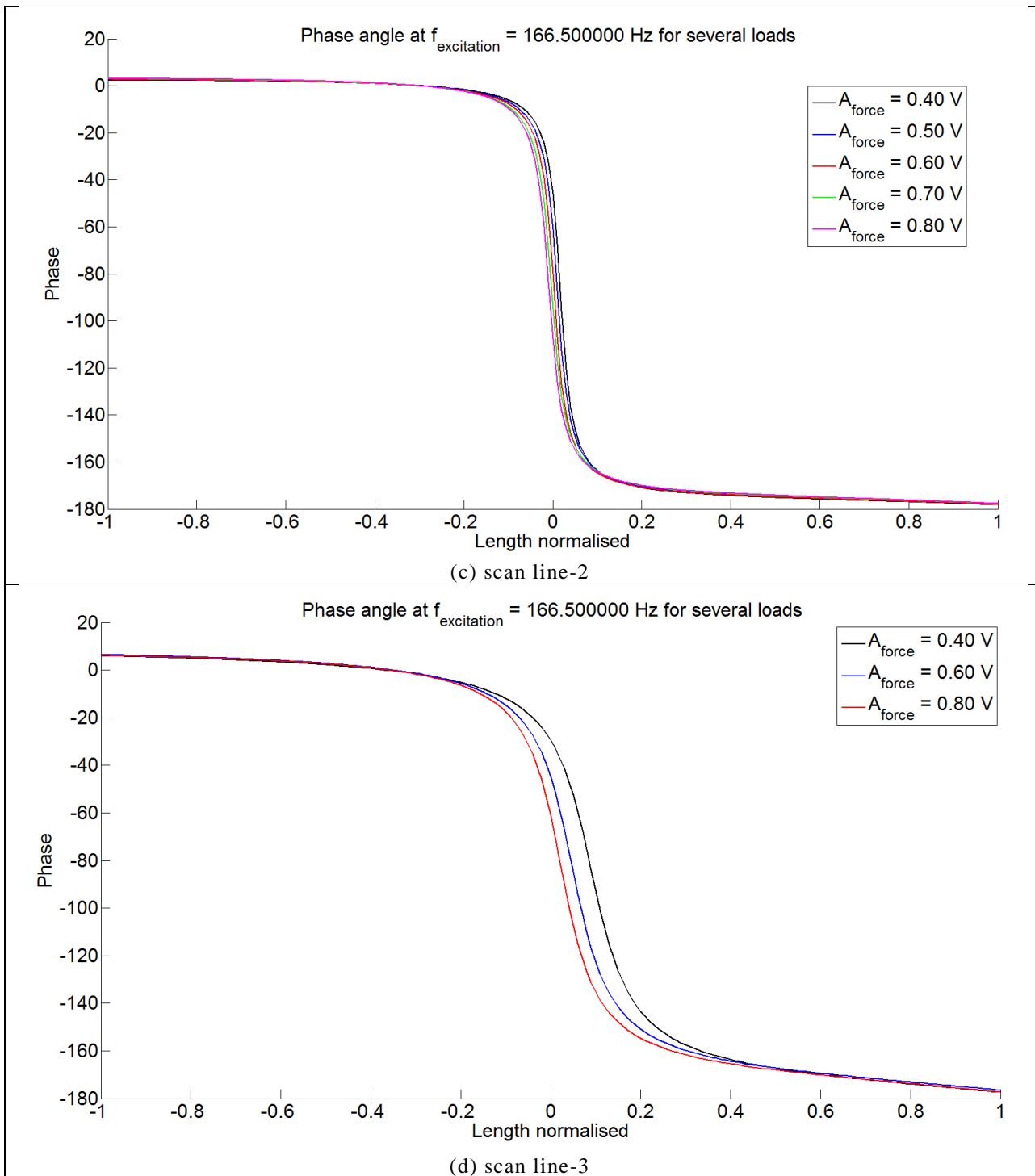
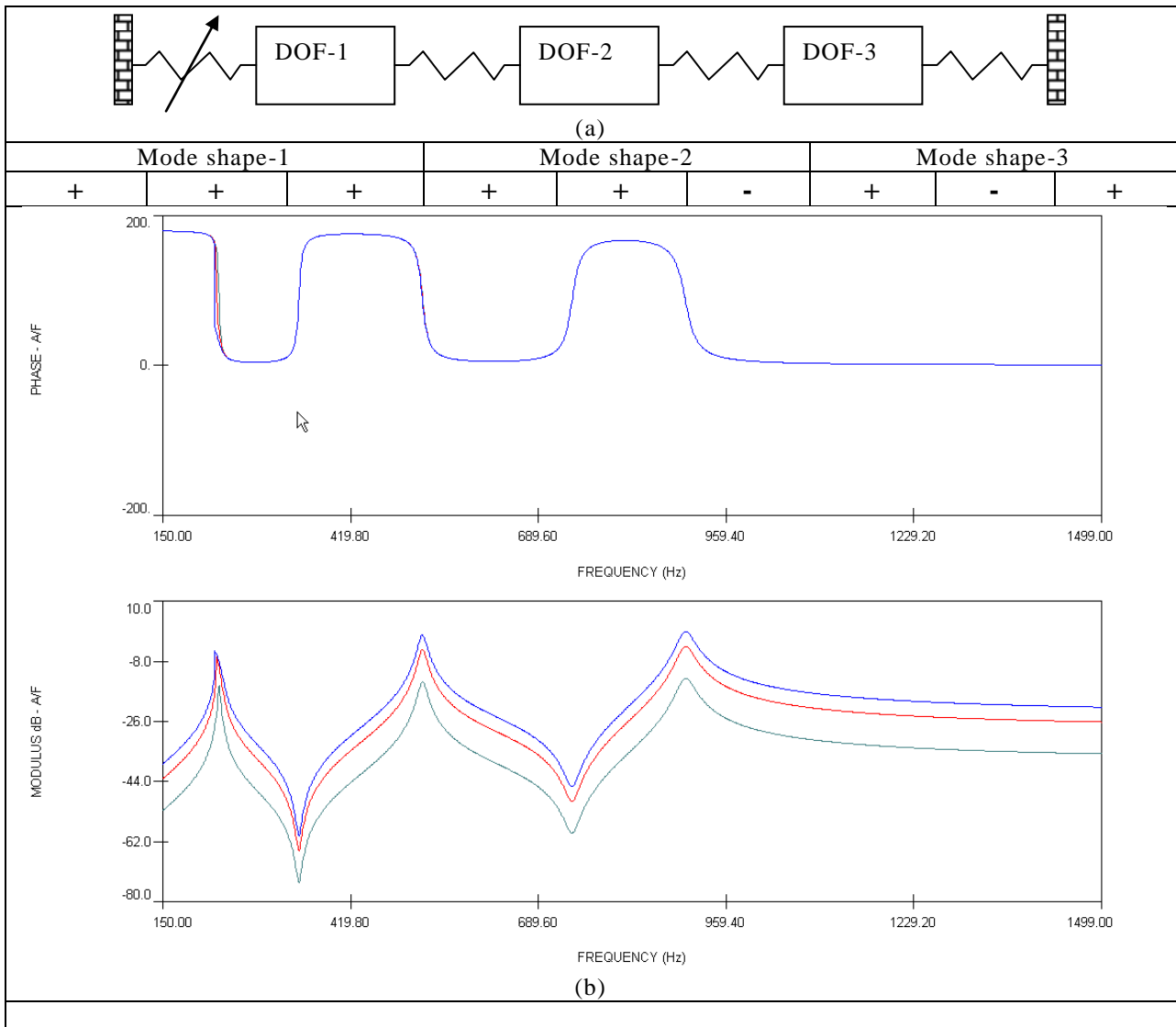


Figure 10 ODSs phase for straight line scans with one bolt removed

## 5. DISCUSSIONS

Before discussing the experimental results, it could be useful to explain where the idea of using response phase for locating nonlinearities came from. As matter of example, this requires the use of a simple 3 Degrees of Freedom system as sketch in Figure 11(a) and the three mode shapes indicated by

(+) and (-), meaning that three (+) are all DOFs moving to the same directions. Figure 11(b) shows the overlap of the responses for three excitation levels, with the drive point to DOF-1. The nonlinearity is setup between the ground and the DOF-1. One can observe from Figure 11(b) that the response phase of the mode shape-1 tends to be more distort than for the other two mode shapes, as it is also clear from the magnitude plot. Let's assume to excite at the frequency of the underlying linear system and to increase the excitation force for three amplitude levels, 1N, 3N and 5N respectively. It is possible to observe from Figure 11(c) that the response phase changes more rapidly for mode shape-1 than for the other two. This is easily explainable by looking at the location of the nonlinear spring, which is very much exercised when all three masses moves synchronously. Despite this example uses a full FRF to show the changes of the response phase, in practical terms this can be executed by measuring ODSs at different vibration amplitudes. Figure 11(d) shows clearly that the nonlinearity is activated for the three DOFs pushing to the same direction.



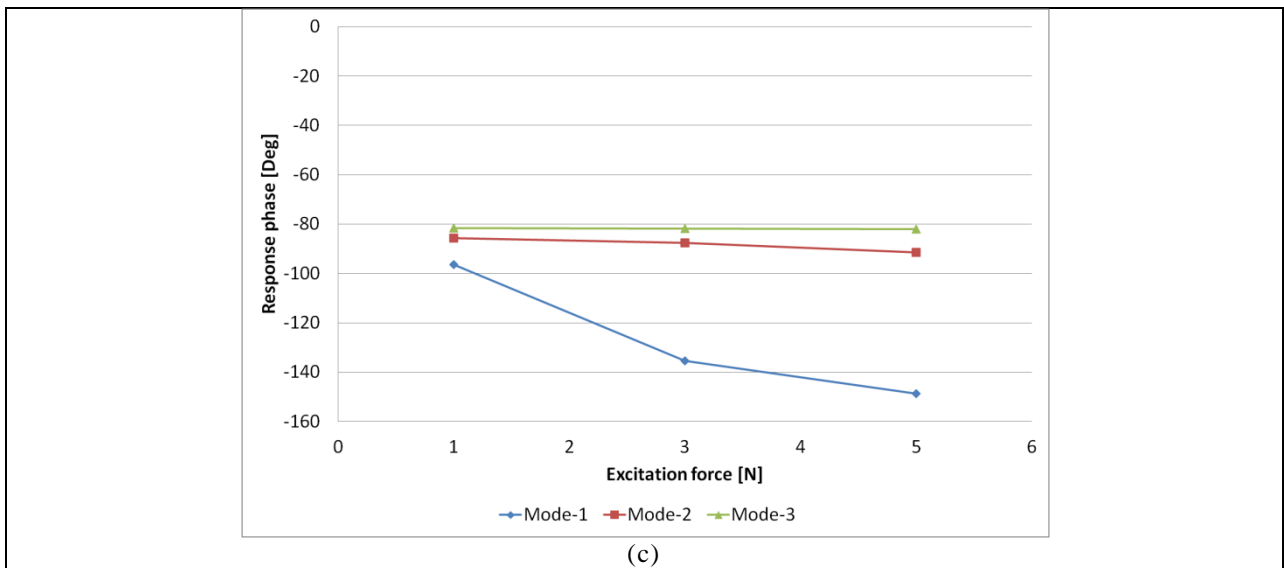


Figure 11

On a similar basis, the experiments produced in this paper aims at locating the nonlinearity by looking at the ODS phase as indicator. The complication in practical situation is that the both temporal and spatial data must be understood in order to evaluate the phase information. In fact, nonlinearities might be activated differently depending on the mode shape excited. Figure 12 shows that the selected second torsional mode changes the phase at the nodal line, which is also very close to the flange position. So, the phase shift tends to be high where the dissipation is also high. Moreover, Figure 10 showed that the phase lag of the ODSs increases as the scanned lines are closer to the vertical nodal line of the torsional mode. This seems to suggest that higher dissipation is measurable at the cross point of the nodal lines.

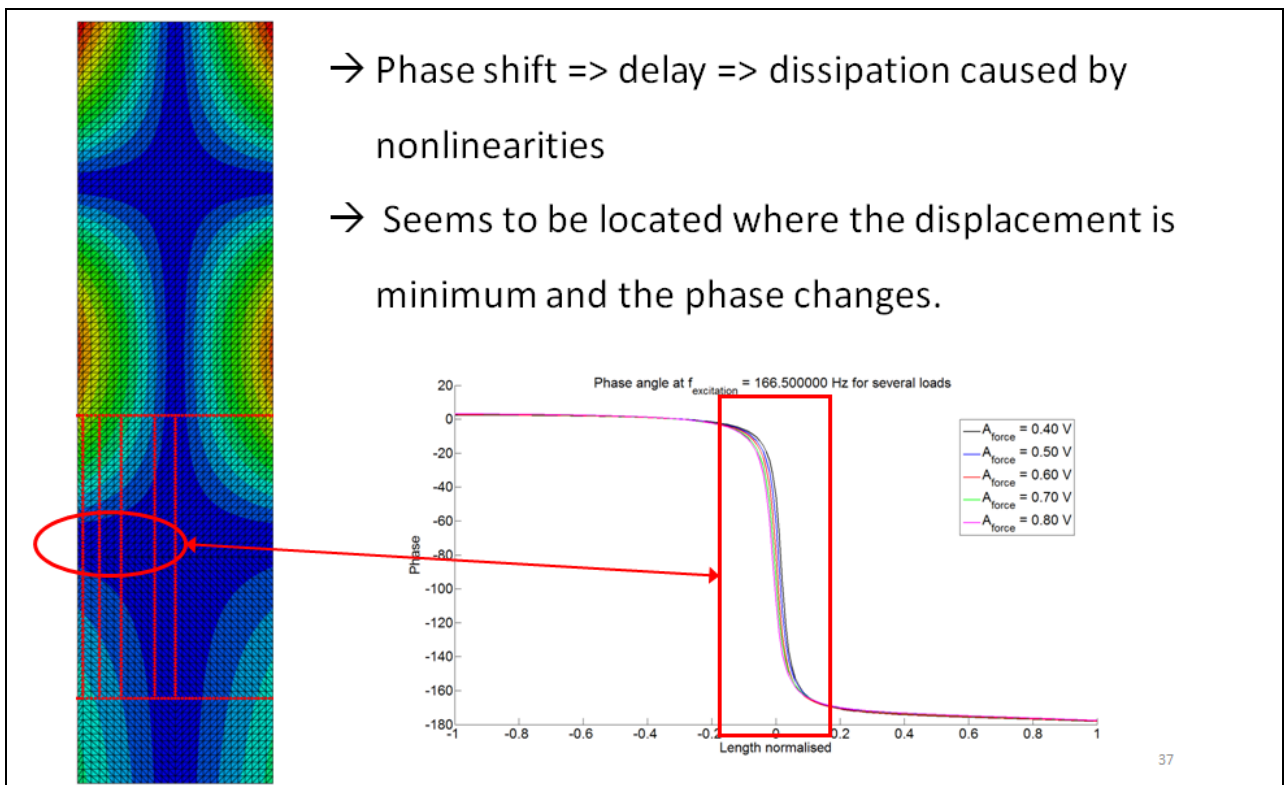


Figure 12 Correlation between mode shape and ODSs phase



## 6. CONCLUSIONS

This paper shows for the first time that response phase mapping from ODS measurements can be used as indicator for locating sources of nonlinearities. The paper presents the use of continuous scanning method for these measurements but even the stepped scan method can be equally a valid technique. The study was focused on a bolted flange but this experimental approach can be extended to any type of mechanical assembly. This study has demonstrated that the response phase shows a shift due to changes of the dynamics of the underlying linear system, in this specific case due to the nonlinear joint behavior. The second torsional mode of the flange shows phase change from  $-\pi$  to  $\pi$  at the nodal line, which is also near the flange position. This occurrence makes the response phase shift visible and easy to correlate with the source of nonlinearity, bolted flange. Experiments were carried out for the other remaining modes but not shown in here. Additional testing and analysis are required in order to understand how to correlate response phase shift, mode shapes and source of nonlinearities. Nevertheless, the SLDV system revealed great potential which can be exploited to the benefit of the dynamicists focused on nonlinear identification.

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