RIGA TECHNICAL UNIVERSITY

Eduards Skuķis

VIBRATION CORRELATION TECHNIQUE FOR CYLINDRICAL STRUCTURAL SAFETY ASSESSMENT

Summary of the Doctoral Thesis

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RIGA TECHNICAL UNIVERSITY

Faculty of Civil Engineering

Institute of Materials and Structures

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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on 17 March 2023 at 14.15 at the Faculty of Civil Engineering of Riga Technical University, 6A Ķīpsalas Street, Room 342.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Eduards Skuķis ……………………………. (signature)

Date: ………………………

The Doctoral Thesis has been written in English. It consists of an Introduction, 3 chapters, Conclusions, 21 figures; the total number of pages is 118, including appendices. The Bibliography contains 64 titles.

CONTENTS

CHAPTER 1: OVERVIEW

1.1. Introduction

Low mass plays a critical role in space missions. Depending on the area of application, it is on average between 10,000 to 20,000 EUR for each kilo of payload to be delivered to space. Therefore, structural mass reduction is a matter of a great effort. Carbon composites allow decreasing the mass of a structure down by 30 % while retaining the same load carrying capacity. All large space agencies, such as ESA for Europe, NASA for the USA or CNSA for China, as well as private providers, such as Space-X or Rocket lab, work on the application of carbon composites to reduce the transportation costs in future. There is intense competition in this field. The early design methods of the spatial single-curvature structures have been utilised for decades while enhancing work and recommendations for the design of more complex structures and complex use as reusable booster launch. Among restricting boundaries are design limit loads that are very sensitive to imperfections and defects, thus there is a clear driving factor for delivering a non-destructive actual limiting force prediction ensuring higher accuracy and reliability for associated risk assessment.

The aim of this Thesis is to investigate the prospects of the Vibration Correlation Technique method (VCT), which allows prediction of actual critical load levels from certain structures and configurations in a non-destructive manner on top of qualification experiments, thus contributing to a rising level of safety.

The principle of VCT method is based on the natural frequency and axial (coaxial) load correlation of a structure. It is based on physical phenomena where natural frequency decrease correlates with each increment of a load and corresponding structural stress level. Once the load reaches the state of buckling, the corresponding natural frequency tends to be equal to a zero for column type structures. While during trials, the natural frequency is measured at increasing load levels, an extrapolation of the predicted ultimate load may be calculated, without reaching the rupture of the structure. Thus, the VCT method may be utilised as an alternative critical load estimation approach ensuring additional safety of a structure considering uncertainties associated with physical specimen. However, in the case of defect-sensitive shells, as those used in space missions, the natural frequency-load interrelation may be highly complex and less robust. Empirical formulas have been developed for metallic-isotropic materials to approximate the correlation. Nevertheless, these formulas cannot be utilised for the design of anisotropic stiffened structures.

It should be noted that similarities in the philosophy of the VCT method can also be observed as natural phenomena. One of the most popular expressions that immediately comes to mind is the expression "the calm before the storm". Thus, before a strong hurricane, the sea becomes surprisingly calm for a while. Despite the intensifying wind, the surface of the water remains even and smooth and there is not the slightest fluctuation on it. Another example of a natural phenomenon that "silences" is volcanoes. If an active volcano nearby suddenly kicks up its activity with steam, smoke, and belowground rumblings, it obviously is erupting, however. Recently researchers have identified that even more dangerous sign is a sudden total silence.

A team led by researchers at Carnegie Institution of Science has been monitoring the seismic activity of more than 50 volcanic explosions in active volcanoes since 2009. At first, they were looking for some pattern in the teeming geological activity before eruptions that could predict explosions. The pattern they found was a lack of activity just in the moment right before an eruption, volcanoes went suddenly and completely quiet and still.

Now that they know about this lull before the eruption, researchers hope to work the information into pre-eruption warnings. Unfortunately, the time provided would be short. Most eruptions had quiet periods of less than 30 minutes, and some had lulls lasting only a few minutes. The longest one measured 10 hours, but then it was also followed by the largest eruption that researchers had seen. This may be a hint for further VCT evolvement.

1.2. **Rationale**

Over the years, the original NASA design recommendations have been used successfully in the design of numerous NASA space vehicles, including the Space Shuttle Solid Rocket Boosters (SRB) and External Tank (ET), as well as the Space Launch System (SLS). However, it has been shown over time that the Knock Down Factors (KDFs) and recommendations provided in the original NASA guideline can result in overly conservative buckling load predictions and designs when applied to these modern aerospace structures. This is primarily because the lower bound KDFs are comprised of test data from cylinders that were manufactured and tested using outdated processes and do not reflect the improvements observed in recent testing of modern aerospace-quality shell structures constructed using advanced materials and reliable manufacturing processes. In addition, the *NASA SP-8007* original monographs were limited to radius/thickness ratios currently driving design of modern structures, such as large integrally machined metallic cylinders or composite cylinders.

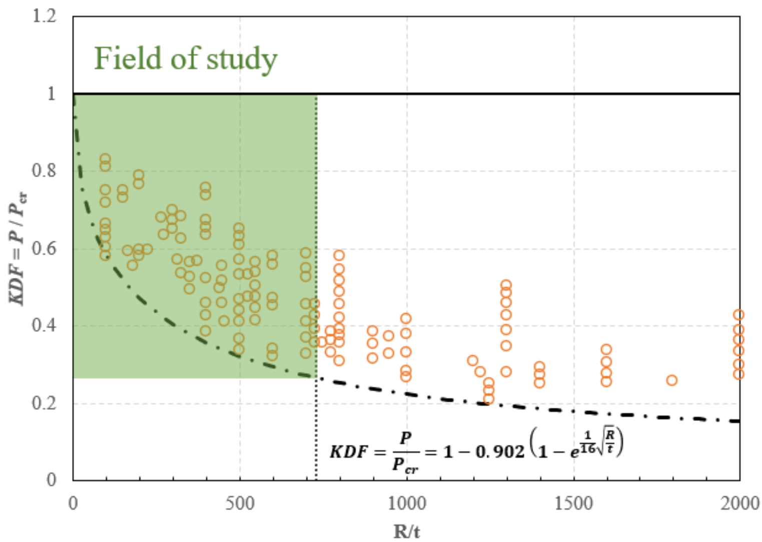


Fig. 1.1. NASA-SP8007 Knock-Down factor curve (Weingarten, 1968).

The main objective of the present Thesis is to extend the reliability of the Vibration Correlation Technique for assessment of imperfection sensitive composite cylindrical structure. By conducting a largest experimental test campaign dedicated to VCT, a particular research aimed to provide a data set for both training and development of surrogate models in formulating a parametrical equation. As it was identified up to now, there is a major gap in statistically reliable set of experimental data, since the studies like NASA/SP-8007 took place in 1968 when composites were neglected. Therefore, assessing of manufacturing signature and testing equipment sensitivity was another objective of current research. Besides experimental research conducted, numerical simulations by Finite Element Method (FEM) and capacities of cloud computing were validated. Therefore, a range of both geometrical and mechanical properties has been covered to develop VCT guidelines assured by statistical credibility. In order to achieve this, there has been an effort to produce a series of CFRP hollow circular cross section columns and cylindrical shells with varying radius/thickness ratios and radius/free height (slenderness) ratios including ply lay-up orientation. It should be noted that R/t ratios are intentionally foreseen to vary between 100 to 750, while slenderness h/R could vary in the range from 8 to 1. With a selected number of lay-ups and boundary conditions, this ensured a statistically meaningful test production batch series (DESICOS, 2019) (NASA, 2019) (ESA, 2019).

1.3. The research Goals

Development of methodology to extend the reliability of the vibration correlation technique for assessment of imperfection sensitive composite cylindrical structure.

1.4. Main statement

The research hypothesis of this thesis was delineated as follows:

1) the correlation exists between the increment of compression load level and the decrease of eigen frequency for cylindrical shells;
2) the vibration correlation method is applicable for isotropic cylindrical shells as well as for orthotropic ones;
3) the modified Arbelo normalisation method for predicting critical load for cylindrical shell by vibration correlation technique is determined with high precision in comparison with the classic approach.

1.5. Scientific novelty

1. The novelty of the dissertation is the developed new method of experimental data normalisation, which is a logical continuation of the Arbelo approach.
2. A radically new approach has been developed and tested to determine the frequency shift under load for cylindrical shells.
3. The reliability of the vibration correlation technique for assessment of imperfection sensitive cylindrical structures has been significantly improved by analysis of results from a large number of experiments performed in this research.

4. Approbation of VCT has been employed for testing of the newest generation space launcher structure including a complex load case scenario.

1.6. Tasks

1. To confirm the correlation between the increase in load level and decrease in frequency for cylindrical shells.
2. To validate the VCT method by manufacturing and experimentally testing isotropic and orthotropic cylinders in a wide range of R/t and R/h ratios.
3. To increase the accuracy of critical load prediction by modifying the normalisation of experimental data.
4. To check the opportunities for applying the VCT method for predicting the critical load of cylindrical shells like evident geometrical defects or other load cases as internal pressure or bending loading.
5. To approbate the VCT method on real-scale objects.

1.7. Structure

Chapter 1: Overview. This chapter describes the scope of the dissertation research. In this chapter, the main research hypotheses and the importance of the novelty of research related to the VCT method are formulated. A brief description of the structure of the dissertation is also presented in this chapter. The list of publications and presentations at international conferences is also displayed in this chapter.

Chapter 2: Methodology. This chapter describes the basic factors necessary for successful prediction of critical load using the VCT method. Three main stages are outlined.

2.1. *Experimental Data Collection.* The experiment procedure is discussed in detail, which, in turn, could be divided into two sub-stages. The factors affecting the critical force are described. The equipment necessary for critical load prediction using the selected methodology is specified, problems faced during VCT data collection are discussed in detail.

2.2. *Data Analysis*. This chapter considers the normalisation options of experimental data to be applied to prediction of critical load using the VCT method.

2.3. *Vibration Correlation Technique Algorithm.* This chapter presents the algorithm for taking measurements using the VCT method

Chapter 3: Main results. This chapter represents publications which reflect the main results obtained during the research and application of the VCT method. The results are published in five cited sources, the total *Impact Factor* is **25** with a total of **155** (2022/09/01) citations in journals indexed in Scopus**.**

Chapter 4: Final remarks. This chapter represents the main conclusions and discussion of the challenges and their solutions with regard to practical application of the VCT method for critical load prediction.

1.8. Publications and approbation

Main results of the Thesis were summarised in five scientific publications. Results of the research were presented at five conferences.

Scientific publications:

1. Kalnins, K., Arbelo, M. A., Ozolins, O., **Skukis, E.**, Castro, S. G. P., Degenhardt R., Experimental non-destructive test for estimation of buckling load on unstiffened cylindrical shells using vibration correlation technique, Shock and Vibration, Volume **2015**, Article ID 729684.
2. Arbelo, M. A., Kalnins, K., Ozolins, O., **Skukis, E.**, Castro, S. G. P., Degenhardt, R., Experimental and numerical estimation of buckling load on unstiffened cylindrical shells using a vibration correlation technique, Thin-Walled Structures, Volume 94, 1 September **2015**, pp. 273–279.
3. **Skukis, E.**, Ozolins, O., Andersons, J., Kalnins, K., Arbelo, M. A., Applicability of the vibration correlation technique for estimation of the buckling load in axial compression of cylindrical isotropic shells with and without circular cutouts, Shock and Vibration, Volume **2017**, 29.
4. Franzoni, F., Odermann, F., Wilckens, D., **Skuķis, E.**, Kalniņš, K., Arbelo, M. A., Degenhardt, R. Assessing the axial buckling load of a pressurized orthotropic cylindrical shell through vibration correlation technique, Thin-Walled Structures, Volume 137, April **2019**, pp. 353–366.
5. **Skukis, E.**, Jekabsons, G., Andersons, J., Ozolins, O., Labans, E., Kalnins, K. Robustness of empirical vibration correlation techniques for predicting the instability of unstiffened cylindrical composite shells in axial compression, Polymers, Volume 12, Issue 12, December **2020**.

Results of the Thesis were presented at the following conferences:

1. **Skukis, E.**, Kalnins, K., Ozolins, O., *Assesment of the Effect of Boundary Conditions on Cylindrical Shell Modal Responses*, 4th International Conference CIVIL ENGINEERING`13, Proceedings Part I, STRUCTURAL ENGINEERING, Jelgava **2013.**
2. **Skukis, E.**, Kalnins, K., Chate, A.*, Preliminary assessment of correlation between vibrations and buckling load of stainless-steel cylinders, Shell Structures: Theory and Applications – Proceedings of the 10th SSTA 2013 Conference, Volume 3,* **2014**, pp. 325–328, 10th Jubilee Conference on "Shell Structures: Theory and Applications", SSTA 2013, Gdansk, Poland, 16 October 2013.
3. **Skukis, E.**, Kalnins, K., Ozolins, O., *Application of vibration correlation technique for open hole cylinders*, Proceedings of the 5th International Conference on Nonlinear Dynamics, ND-KhPI2016, September 27–30, **2016**, Kharkov, Ukraine.
4. **Skukis, E.**, Ozolins, O., Adersons, J., Kalnins, K., Arbelo, M. A.*, Experimental Test for Estimation of Buckling Load on Unstiffened Cylindrical Shells by Vibration Correlation Technique, Procedia Engineering,* Volume 172, **2017**, pp. 1023–1030, 12th International

Conference Modern Building Materials, Structures and Techniques, MBMST 2016, Vilnius, Lithuania, 26 May 2016.

5. **Skukis,** E., Kalnins, K., Jekabsons, G., Ozolins, O., *Benchmarking of vibration correlation techniques for prediction of buckling load of cylindrical shells,* 16th European Conference on Spacecraft Structures, Materials and Environmental Testing (ECSSMET), **2021.**

CHAPTER 2: METHODOLOGY

This section represents three main stages necessary for VCT prediction of the critical load:

- VCT experimental campaign: It is divided into two experimental approaches, which are necessary to carry out the prediction by the VCT method.
- Pre-selection of excitation, field of view of measurements and setting as well as other required data for further VCT analysis.
- Data analysis: This is the process of normalisation of experimental data, calculation and prediction of critical force using the method.

2.1. Experimental data collection

This section provides a description of the procedures executed during the experimental campaign, which can be divided into two main groups: shell buckling tests and experimental modal analysis, as shown in Fig. 2.1.

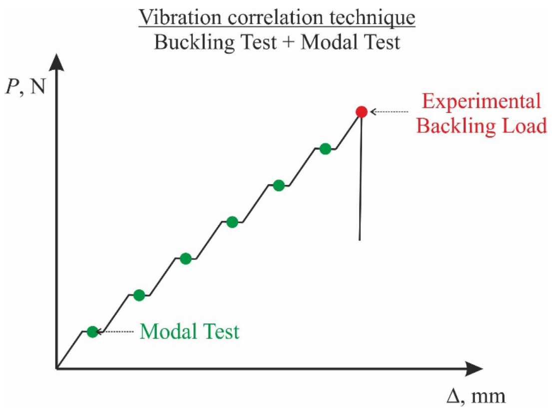


Fig. 2.1. Experimental VCT testing – step loading.

2.1.1. SHELL BUCKLING EXPERIMENTS

The universal quasi-static testing machine is necessary for conducting buckling tests (Degenhardt, 2007). The main task of this equipment is to load a sample until the set load is reached and to maintain this load over the time while the measurement of cylinder vibrations is made (Fig. 2.1). Another important aspect is preliminary determination of basic frequencies using a quasi-static testing machine to avoid resonance with the tested sample during testing. The opportunity to control the load via travel allows avoiding destruction of the tested piece during testing, which is also very relevant in order to be able to conduct a repeated experiment on the cylinders made from a composite material (Zimmermann, 2006; Wilckens, 2020).

The main machine used in the majority of experiments is the universal quasi-static testing machine Zwick 100. This equipment has certain limitations – the maximum diameter of the testable cylinder is 500 mm and maximum height is 1000 mm, the load also is limited to 100 kN.

Boundary conditions can be of two kinds. The first kind includes the boundary conditions for fixation of a cylinder in the testing machine. The first experiments were carried out with the cylinders placed between two plates. The upper plate was screwed tightly to the testing machine, a hemispherical joint was installed on the bottom plate, enabling rotation of the supporting plate, thus eliminating bending moments and, hence, promoting self-alignment of the cylinder axis with the loading direction, as shown schematically in Fig. 2.2.

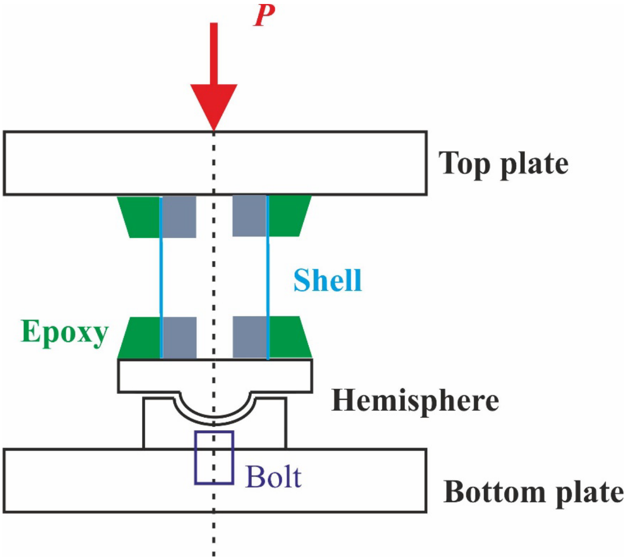


Fig. 2.2. Schematic of the setup for compression tests of cylinders, testing using a hemispherical joint.

Due to complexity of hemispherical modelling in the analytical model and the problems caused by single-side loading of a cylinder, i.e., at the moment of buckling, the sphere was compensating the load and further destruction was localised at the place with the biggest defect. In general terms, it was not possible to determine the buckling shapes over the whole surface of the cylinder. Thus, changes were made in the boundary conditions. Both the top and bottom edges of the shells resting on the respective machine plates were joined to the plates by means of potting with a resin/powder filler to eliminate loading imperfections and contact surface misalignments. The test set-up contained a shimmed interface at the lower machine plate (Fig. 2.3). Shimming was performed by placing very thin sheets of metal between the lower loading plate and the load-distributing washer attached to the load frame in order to eliminate the small gaps between both surfaces, so that an even distribution of load along the cylinder's circumference was ensured.

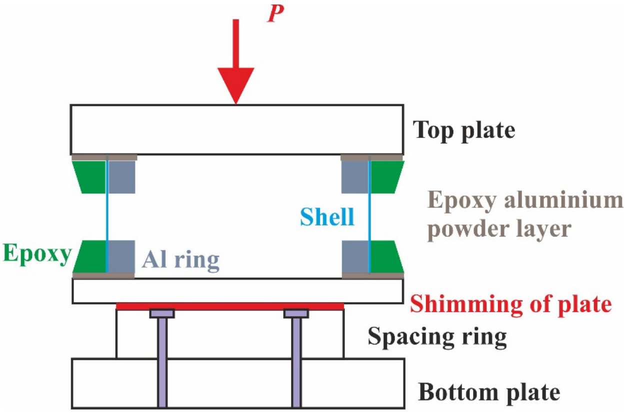


Fig. 2.3. Schematic of the setup for compression tests of cylinders, testing using the shimming of the plate.

Such an approach to boundary conditions results in dependence on an operator, a person who will install a cylinder for testing, and reduces the opportunity for repeatability of result. Having analysed the experiments conducted by the partners from DLR, boundary conditions were optimised, the bottom plate was bolted to the respective crosshead, as shown in Fig. 4.

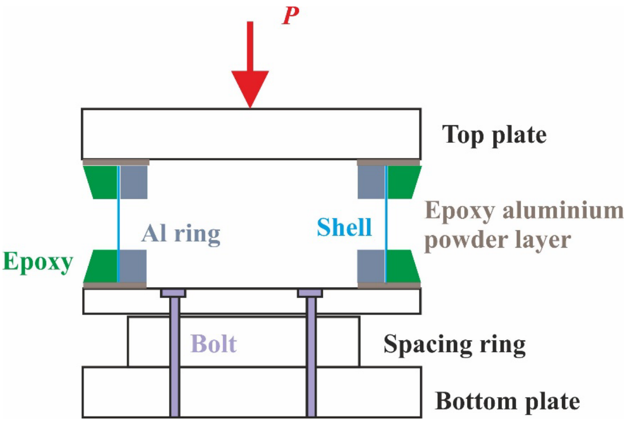
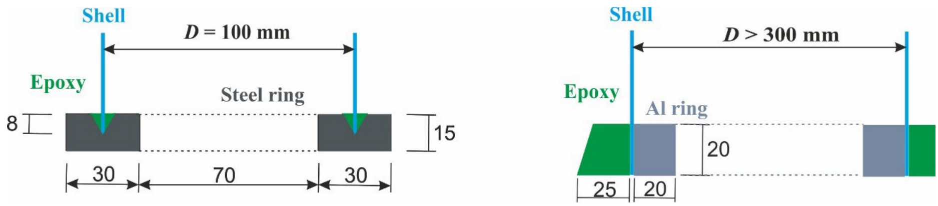


Fig. 2.4. Schematic of the setup for compression tests of cylinders, testing using the shimming of the plate.

The second kind includes the boundary conditions of the cylinder itself (Lancaster, 2000). Edges of the 100-mm-diameter shells were mounted between parallel steel rings, in 8 mm deep circular grooves with a V-shaped cross section, which were filled with a mixture of epoxy resin and fine sand, as schematically presented in Fig. 2.5 (a). The top and bottom edges of the 100-mm-diameter shells were both clamped by aluminium rings from the inside and potted with an epoxy mortar containing fine sand and slag (Fig. 2.5 (b)).



(a) (b)

Fig. 2.5. Schematic of the mounting of cylinders: (a) in the groove of a steel ring; (b) potting onto plates of the test machine. Dimensions in the figure are given in mm.

The results and impact of these tests will be considered in the next chapter. Optimization of boundary conditions was carried out to increase the experimental critical load, as well as to simplify the finite element model. Calculation using the finite element method is necessary to determine the linear buckling load (Castro, 2014;Wagner, 2017), which further is applied to the VCT-based prediction of the critical load.

2.1.2. THE EXPERIMENTAL MODAL ANALYSIS

The experimental modal analysis (EMA) is the most widely used procedure for such investigations (Maia, 1997; Kjær, 2022). It provides the frequency response functions (FRFs) of the system using known input excitation forces and the corresponding measured output vibrational responses. The experimental equipment for the measurements of vibrations and building of shapes of fluctuations is manufactured in a great variety. One the most widespread ways to measure vibrations is a vibrosensor – a contact method (ISO7626-2, 2015). Measurements are taken in a fixed place, with a vibrosensor installed inside (Zhang, 2008). Such an approach is relatively inexpensive, it allows acquiring continuous images of vibrations in a temporal response, but it features a range of bottlenecks, such as additional mass on the tested item (Wesolowski, 2010). The problem is to acquire the shapes of fluctuations, which are needed for control of the classical VCT method. The problem is that it is necessary to produce agitation in different pre-set locations, and this results in increased timing for the EMA.

There are also several different possibilities to start vibrations on a cylinder: piezoelectric actuator, modal shaker. All these actuators change boundary conditions and add mass to the tested item. Agitation produced by an impact hammer can result in an earlier buckling failure of a cylinder as well as increases the time required to acquire fluctuation shapes. Nevertheless, all options mentioned above are appropriate for application when there is a clear concept of the results to be obtained also within the limited budget. The solution to these problems is to use non-contact response transducers (sensing devices). The laser-based optical transducers can successfully substitute the traditional piezoelectric type of transducers and eliminate any additional mass coming from sensing devices. The most recently useable laser transducers are based on the Doppler velocimetry principle and they have attracted attention of many researchers dealing with experimental modal analysis. A highly sensitive optical system is therefore used for vibration sensing – POLYTEC Scanning Laser Vibrometer system PSV- 400

(Theory, 2008; Polytec, Laser Doppler vibrometry, 2022) Later, an opportunity to compare the performance of the Laser Vibrometer system PSV-500-3D appeared. Figure 2.6 shows a typical VCT set up.

The following parts are involved in the following measurement chain:

- source of excitation signal (generator);
- power amplifier;
- exciter-loudspeaker;
- vibrometer system PSV-400 and PSV-500-3D;
- analyser (PC system).

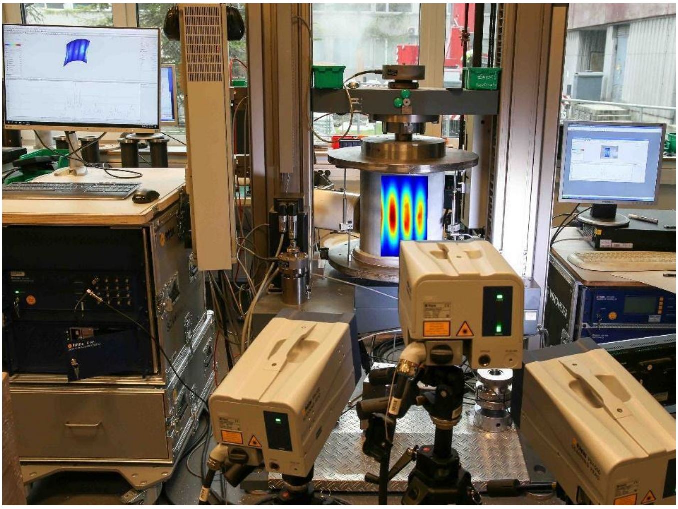


Fig. 2.6. Typical VCT test set up.

SCANNING LASER VIBROMETER: PSV-400

The PSV-400 operates on the Doppler effect measuring frequency changes of the back scattered light wave from a vibrating object. If a wave is reflected by the vibrating object and detected by the laser vibrometer, the measured frequency shift of the wave can be described as

$$\Delta f = \frac{2\vec{v}\cdot\vec{e}}{\lambda} = \frac{2v}{\lambda}\cos\ \theta\ , \tag{2.1}$$

where v is the object's velocity and $\lambda = 633$ nm is the wavelength of the emitted wave. To determine the velocity of an object, the Doppler frequency shift has to be measured at a known wavelength. This is done by a laser interferometer.

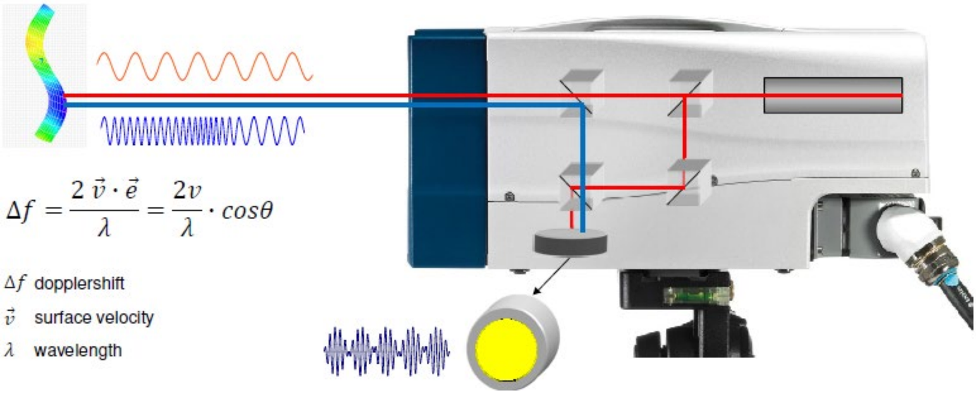


Fig. 2.7. Technological background (Polytec, Polytec Scanning Vibrometer, Theory Manual. PSV, PSV-3D, MSA/MSV, as of Software 8.5, 2001).

SCANNING LASER VIBROMETER PSV-500-3D

The main principle of the work of the scanning laser vibrometer PSV-500-3D is also based on the Doppler effect (Fig. 2.8). A distance gauge in the main head is an extra, which allows changing the object's geometry; this function was also available earlier, but it was necessary to integrate the distance gauge as a separate unit mounted outside the chamber. Scanning of the geometry has an accuracy of approximately 1 mm, depending on the quality of the reflected surface. The basic characterising features are:

- 3 synchronised laser scanners with the common control;
- laser beams intersect on the surface;
- geometry is imported or measured;
- simultaneous measurement of 3 vibration components;
- coordinate transformation in object coordinate system.

An additional difference is an opportunity to measure its own point with each head, i.e., to acquire three vibro results at a time. Also, only one head may be used for measurements, same as with the previous model PSV-400 with the only difference – the geometry data of the scanned cylinder will be acquired.

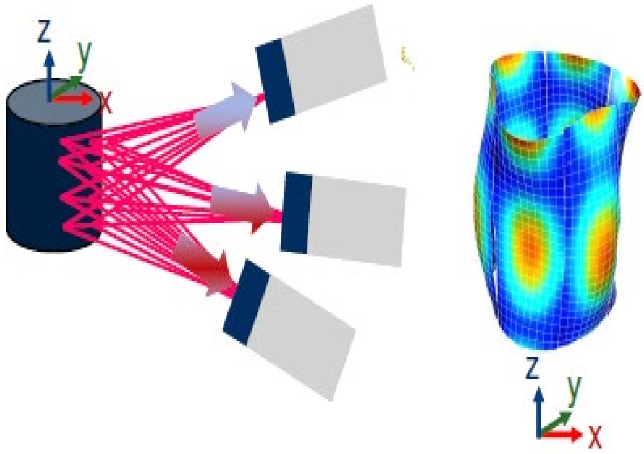


Fig. 2.8. Working principle of PSV-500-3D (Polytec, Polytec PSV-E-500 Operating Instructions Manual, 2016).

2.1.3. VIBRATION SPECTRA AND MODES

As it has been mentioned above, the VCT-based prediction needs measurements of the natural frequency at a fixed load, i.e., it is necessary to follow up the changes in the natural frequency under loading. As far as there are a great number of natural frequencies, the range of measurements is the first limitation (Hamidzadeh, 2009). The example of a frequency response is given in Fig. 2.9. Frequency peaks of low amplitude at the beginning of the response are exactly the natural frequencies of the structure, floors and walls. It is important to keep monitoring that during the testing the natural frequency of a cylinder does not approach them. After 200 Hz, for this sample, the natural frequencies to be monitored emerge.

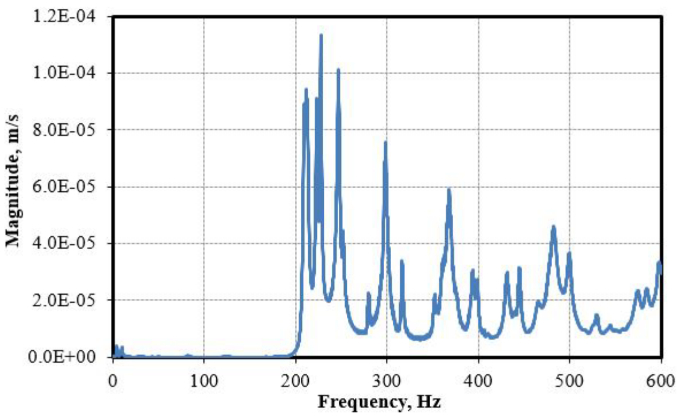
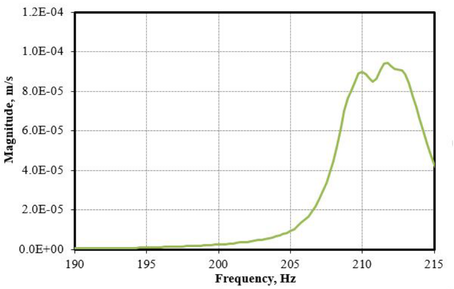
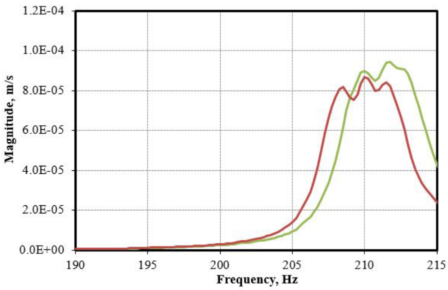


Fig. 2.9. Frequency response.

Every frequency has its shape of fluctuations and it is important to understand that at the changes under loading one and the same form of fluctuations is monitored. What kind of problems may occur here? There are indeed many bottlenecks. In the ideal world in the case of an ideal cylinder, the frequency will have two symmetric shapes of fluctuations. In the world of experiments, these shapes of fluctuations will be separated, i.e., will be distant, but it is not always the case, as these symmetric shapes also can be absent, see Fig. 2.10 a). In a similar manner, due to the vicinity of other shapes of fluctuations, changes in the sequence of shapes of fluctuations under loading can occur, which are complicated to monitor only by the frequency response (Fig. 2.10 b)).



a)



b)

Fig. 2.10. Frequency response with two modes of one frequency.

Consequently, it is necessary to control the shape of fluctuations and its change under loading.

The following problem is in the fact that the chosen shape of fluctuations can disappear under loading, as shown in in Fig. 2.11. The higher the natural frequency, the higher is the chance of such an effect; besides, new natural frequencies appear at these high frequencies.

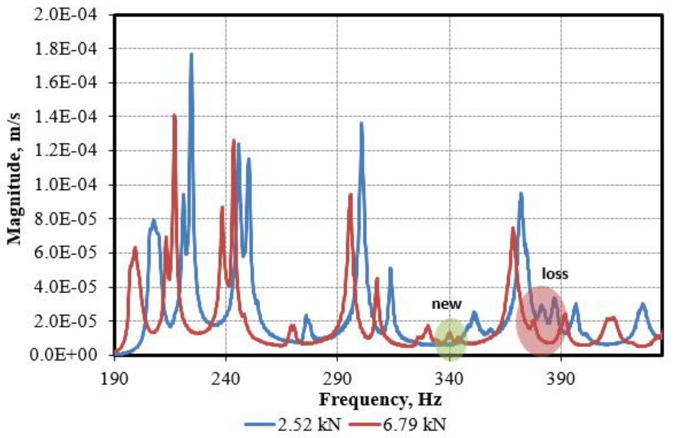


Fig. 2.11. Frequency response, example loss and new eigen frequency.

Every natural shape of fluctuations has its designation (*m, n*) – numbers of neutral lines by axis x and y. The example of such natural shapes of fluctuations under and without loading is shown in Fig. 2.12 (Avieable, 2022). The complexity of calculation of *m* – the number of vertical neutral lines from an experiment – is caused by the number of partial peaks, correlation of their surface areas to the total surface area of the cylinder. It is easier to calculate the number of horizontal lines *n*. Using PSV-500-3D, the natural shape of fluctuations can be acquired for the whole cylinder over the entire diameter, but the time required for this is disproportionately long compared to the benefits that can be gained from the acquired information.

There is a numerical algorithm based on the modal assurance criterion (MAC) (Pastora, 2012) used to identify the variation of each vibration mode during axial loading; the MAC index performs a comparison between two vectors of the same length and the index returns a value close to one if a linear relationship between the two vectors exists and near zero if they are linearly independent, which was applied to monitoring of a certain shape of fluctuations of a large number of cylinders. The result is available at vct.rtu.lv and published in one of the articles.

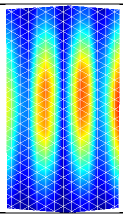
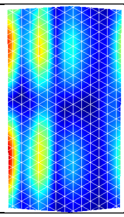
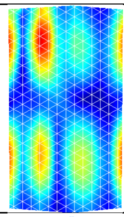
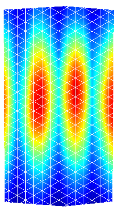
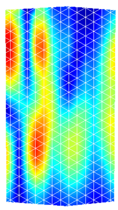
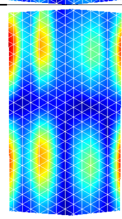
Load, kN	Mode	*f*, Hz	Mode	*f*, Hz	Mode	*f*, Hz
0.0		211.75		394.25		431.50
4.96		202.75		378.00		416.75

Fig. 2.12. Eigen modes without and with load.

The answer to the first question regarding the parameter to be measured is that the changes under loading of the first natural frequency for a certain shape of fluctuations acquired experimentally, which manifests itself over the entire range of loading, are measured or, actually, monitored. Indeed, it may be observed in the published works that the monitoring was performed also for other natural shapes of fluctuations, although it did not bring any significant improvement of the result with application of the normalisation technique, which will be discussed below.

The measurements are taken on the surface of the cylinder, as it has been described above, every shape has its zero lines, and it is logical that the information acquired from such sectors will be of a low quality. The example is shown on the frequency response presented in Fig. 2.13.

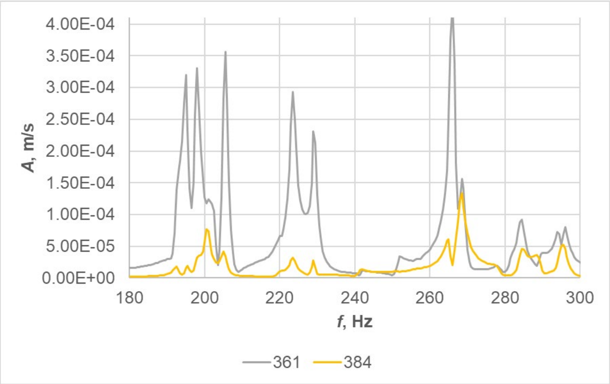


Fig. 2.13. Frequency response with bad and good measurement points.

The number of measured points has an impact on the time required to measure modal characteristics and accuracy of the shape of fluctuation. One more factor that influences the time of experiment is sampling frequency. This factor directly depends on the value of the first frequency. The lower the first frequency, the higher sampling frequency is required. A simple example may be presented: at $\Delta f = 0.25$ Hz the measurement must be made in one point at $(1/\Delta f)$ 4 sec. This value should be multiplied by the number of points, adding the time of transit from one point to another, adding a repeated measurement if the point differs from others by response. This makes the overall time required to measure one position for the VCT prediction. Thus, within 10-minute testing, approximately 120 points can be measured from the surface at $\Delta f = 0.25$ Hz. The questions whether 120 points are a lot or little and whether 10 minutes is a long time arise. There is no single answer to these questions. This parameter depends on the size of a tested item and sampling frequency. It is also necessary to account for load relaxation during testing, i.e., the load decreases during testing.

The number of positions is another important factor to measure the natural frequency at different loads. It is necessary to determine how close to the value of the experimental critical load measurement should be made. At the initial stage of familiarisation with the VCT method, measurements were taken at up to 50 % of the experimental critical load. Tolerance of prediction of the critical load exceeded 10 %, which was unacceptable. The bottle-neck is that before the buckling test, the experimental critical load is unknown. The experiments were carried out on the metal cylinders that may not be retested after buckling failure, but the main goal of the research was to determine the maximum critical load and to become aware of an opportunity to measure the data for the VCT prediction. Later, the testing was carried out on the carbonic cylinders appropriate for multiple testing. It has been discovered that the VCT method is becoming more precise in predictions of the critical load approaching to the experimental critical force in terms of load, as shown in Fig. 2.14, at the experimental critical load of 25.04kN.

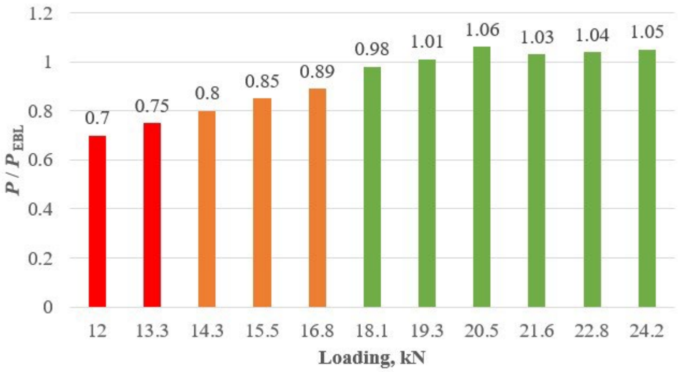


Fig. 2.14. Buckling load prediction using the VCT approach for different loading ranges.

One more important factor to be considered is the first data used in the VCT-based prediction at low loading close to 0 kN. It was noticed that during some experiments, frequency at loading was higher than that at a lower loading, see Fig. 2.15 for data on Cyl.6N. Besides, demonstrative behaviour at the initial stage can be observed in case of Cyl.4N, when abrupt decrease of frequency occurs compared to further loading. Such behaviour, most likely, points at some problems in the boundary conditions.

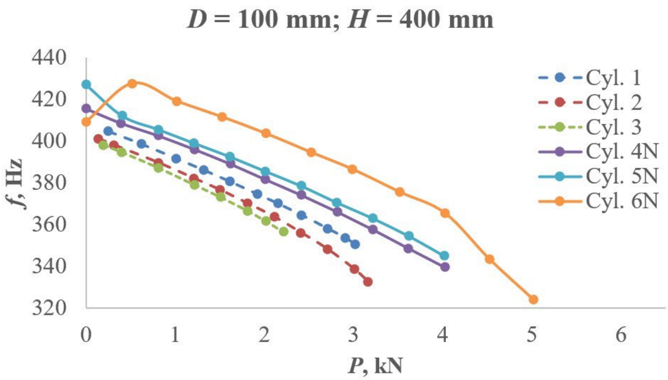


Fig. 2.15. Anomaly at the initial testing stage.

2.2. Data analysis

The concept of relating the buckling load of the structure to the load level in which the fundamental natural frequency is zero has been known for more than a century, it is attributed to Sommerfeld (Somerfeld, 1905). Nevertheless, only in the 1950s, this concept was first considered for estimating the buckling load through a non-destructive experimental procedure (Lurie, 1952; Johnson, 1953). The first VCT studies were based on the linear relationship between the axial load level and the square of the loaded natural frequency, which can be demonstrated for fully simply supported columns, plates (Johnson, 1953), and cylindrical shells (Leissa, 1973; Virgin, 2007):

$$f^2 + p = 1\,, \tag{2.2}$$

where f is the ratio between the loaded natural frequency $\underline{\omega}_{mn}$ and the unloaded natural frequency ω_{mn}, both associated with the same vibration mode defined by axial half-waves m and circumferential waves n (for cylindrical shells), and p is the ratio between the applied load P and the linearized buckling load P_{CR} (from an eigenvalue buckling analysis or theoretical buckling equations).

Based on Eq. (2.2), direct and indirect VCT approaches were proposed throughout the last 7 decades (Singer, 2002); a complete review of this research effort is available in the quoted book. The indirect methods imply assessing the actual boundary conditions through the VCT test campaign aiming to update an initial model. This methodology improves the estimation of the buckling load; an example of an indirect method based on Eq. (2.2) is found in (Singer, 1979). The direct methods are based on an experimentally determined functional relationship between the applied load and the loaded natural frequency to directly estimate the buckling load, see (Radhakrishnan, 1973; Souza, 1983; Arbelo, 2014) among others.

The classic direct VCT method consists of plotting the characteristic chart f^2 versus p and calculating the best-fit linear relationship between the experimental data. In this method, the buckling load is extrapolated as the load level associated with zero magnitude of the loaded natural frequency (Lurie, 1952; Johnson, 1953; Singer, 2002). Even considering that the linear relationship does not hold in the presence of other than fully simply supported boundary conditions, the method presented proper estimations for columns with different boundary conditions in the experimental campaigns (Lurie, 1952; Burgreen, 1961; Chailleux , 1975).

Based on the detailed bibliographic review provided in (Singer, 2002), it may be concluded that the classic VCT approach applied to plate structures is straightforward in case of imperfection-insensitive structures. For examples, Lurie (Lurie, 1952) did not validate it considering simply supported flat plates during the 1950s, Chailleux et al. (Chailleux, 1975) succeed in estimating the buckling load of simply supported flat plate specimens with small imperfections during the 1970s and, recently, Chaves-Vargas et al. (Chaves-Vargas, 2015) applied the linear approach for flat carbon fibre-reinforced polymer stiffened plates.

Different authors proposed modified VCT approaches addressing imperfection-sensitive structures like curved panels and cylindrical shells (Singer, 2002). In the 1970s, Radhakrishnan (Radhakrishnan, 1973) proposed a method based on the extrapolation of the final linear path of the classical characteristic chart to the applied load axis; the author obtained exact results considering the last two measured points for tubes made of Hostaphan®.

Segal (Segal, 1980) investigated 35 existing VCT experiments of stiffened cylindrical shells. The author adjusted an optimal parameter q_{OPT} to raise the natural frequency F, in which a linear best-fit would lead the load level associated with zero natural frequency magnitude to the experimental buckling load:

$$F^{q_{OPT}} = A - BP, \tag{2.3}$$

where A and B are fitting constants.

A functional relationship between the optimal parameter q_{OPT} and the main geometric characteristics of stiffened cylindrical shells was proposed. This study achieved a substantial reduction in the scatter of the VCT estimated knock-down factors (KDF) when compared to the indirect VCT method based on Eq. (2.2). The same Eq. (2.3) was investigated for upper and lower bounds of the optimal parameter q_{OPT} and, hence, of the estimated buckling load.

A novel approach for imperfection-sensitive stiffened cylindrical shells was proposed in (Souza, 1983). The authors suggested a modified characteristic chart based on the parametric forms $(1 - p)^2$ and $1 - f^4$, in which a linear relationship is expected, as presented in Fig. 2.16, the schematic view of the VCT proposed in (Souza, 1983), that reproduces the results from (Souza, 1983) for illustrating the VCT.

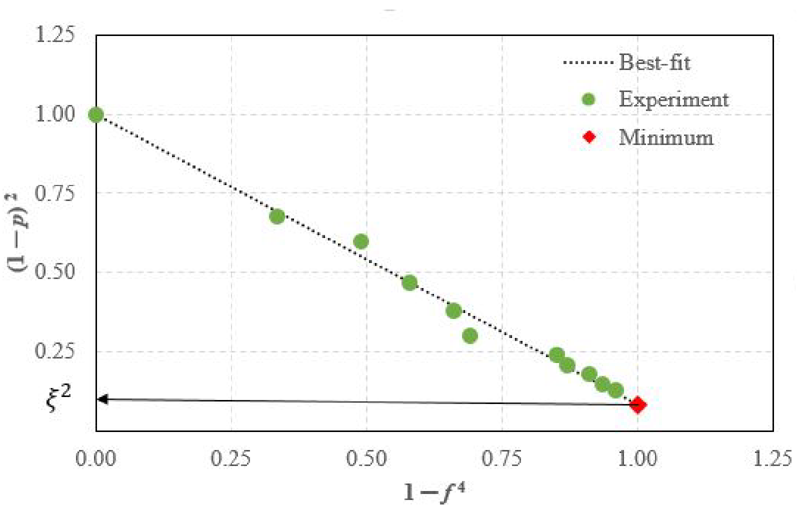


Fig. 2.16. Schematic view of the VCT proposed in (Souza, 1983).

In this VCT method, the linear relationship is obtained through a best fit procedure and it is considered for evaluating the parametric form $(1-p)^2$ when the loaded natural frequency is zero $1 - f^4 = 1$ in the frequency parametric form therefore, the method can be expressed as:

$$(1-p)^2 + (1-\xi^2)(1-f^4) = 1, \qquad (2.4)$$

where ξ^2 is the magnitude of $(1-p)^2$ when $1 - f^4$ equates one and it represents the square of the drop of the load-carrying capacity due to initial imperfections. Based on ξ^2, the VCT estimation of the buckling load P_{VCT} is:

$$P_{VCT} = P_{CR}\left(1 - \sqrt{\xi^2}\right). \qquad (2.5)$$

From Eq. (2.5), the term $1 - \sqrt{\xi^2}$ can be considered as an experimental estimation of the KDF γ of conventional sizing approaches (Weingarten, (Revised 1968), 1965). Another method considering stiffened cylindrical shells was proposed in (Souza, 1991). The authors approximated the classic characteristic chart as a cubic parametric curve. They also suggested the Hermite form for defining the parametric equations. The described methods (Souza, 1983; 1991) were both validated considering the experimental results of stiffened cylindrical shells tested at Technion (Singer, 1980).

Similarly, the classic characteristic chart was represented by a second-order equation in (Abramovich, 2015). The authors adjusted the second-order best-fit relationship applied to curved stiffened panels. An assessment of the estimated buckling load accounting for load levels up to 50 % of the linear buckling load showed reasonable results. Nevertheless, for improving the estimations, the authors suggested load levels near the typical sharp bend of the classic characteristic chart.

In 2014, Arbelo et al. (Arbelo, 2014) modified the work done by Souza et al. (Souza, 1983) proposing a novel VCT based on the characteristic chart between the parametric forms $(1-p)^2$ and $1-f^2$. The authors empirically verified a second-order relationship as illustrated in Fig. 2.17, which reproduces the results from (Arbelo, 2014) for a schematic view.

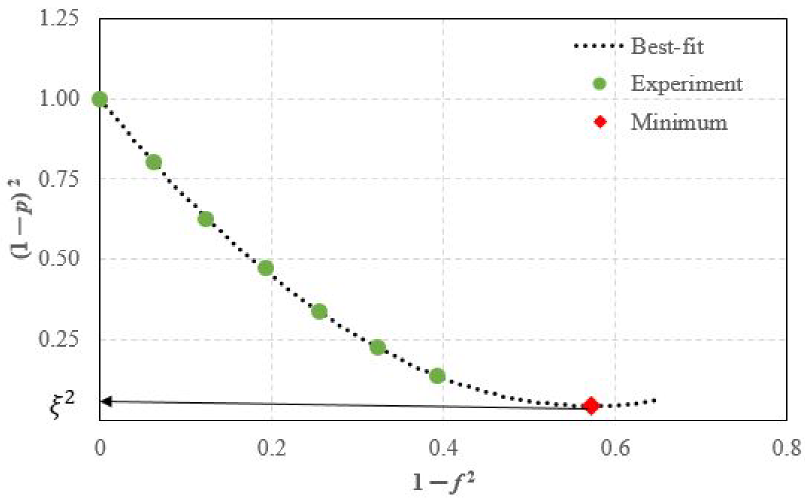


Fig. 2.17. Schematic view of the VCT proposed in (Arbelo, 2014).

The second-order equation is obtained through the best-fit procedure and it is considered to evaluate ξ^2 as the minimum value of the $(1-p)^2$ axis. Mathematically, the method is formulated as:

$$(1-p)^2 = C_2(1-f^2)^2 + C_1(1-f^2) + C_0\,, \tag{2.6}$$

where A, B and C are the fitting coefficients and ξ^2 is calculated as:

$$(1-p)^2 = \xi^2 = -\frac{B^2}{4A} + C. \tag{2.7}$$

The estimated ξ^2 is considered for the buckling load estimation as presented in Eq. (2.5). It is worth mentioning that this method does not depend on the similarities between the buckling and the vibration modes but on the effects of the initial imperfections on the loaded frequency magnitude.

The above-presented method has been validated through 8 experimental campaigns (Arbelo, 2015; Kalnins, 2015; Skukis, 2017; Franzoni, 2019; Shahgholian Ghahfarokhi, 2018; Labans, 2019; Franzoni, 2019) considering metallic and laminated composite cylindrical shells with different design details: unstiffened (Arbelo, 2015; Kalnins, 2015; Skukis, 2017; Franzoni, 2019), with and without cut-outs (Skukis, 2017), grid-stiffened (Shahgholian Ghahfarokhi, 2018), with closely-spaced stringers and internal pressure (Labans, 2019), and manufactured considering variable angle tow (Franzoni, 2019).

In 2020, Skukis et al. (Skukis, 2020) modified the work done by Arbelo et al. (Arbelo, 2014) proposing a novel VCT based on the characteristic chart between the parametric forms $(1-p)^2$ and $1-f$. The authors empirically verified a second-order relationship as illustrated in Fig. 2.17, which reproduces the results from (Skukis, 2020) for a schematic view.

Since the form of the right-hand side of Eq. (2.6) has been arrived at empirically, it appears plausible that similar functions with this property can be used to locate the instability onset. An empirical modification of Eq. (2.6) employing a second-order polynomial of $1-f$ was considered:

$$(1-p)^2 = c_2(1-f^2)^2 + c_1(1-f) + c_0\,. \tag{2.8}$$

Then, the minimum value of $(1-p)^2$ as a function of $1-f$ is given by

$$\frac{d(1-p)^2}{d(1-f)} = 2(1-p)\frac{dp}{df}\,, \tag{2.9}$$

i.e., the condition $dp/df = 0$ holds at the critical load. The relationship is illustrated in Fig. 2.18.

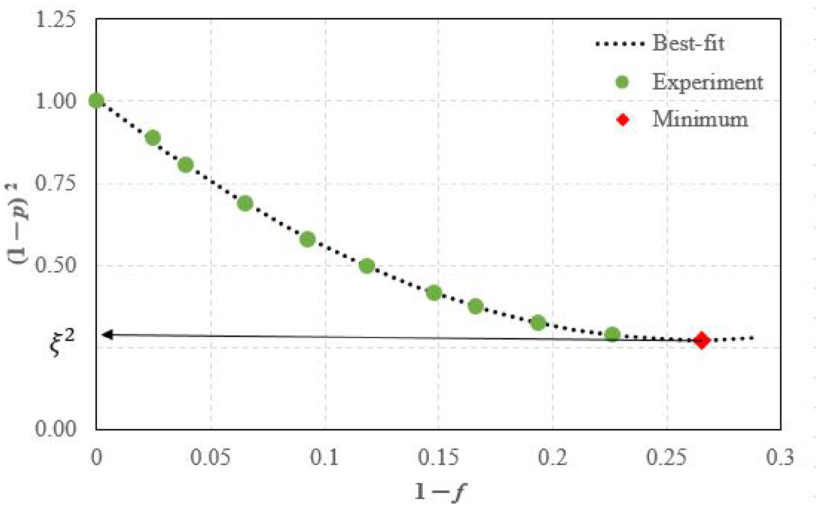


Fig. 2.18. Schematic view of the VCT proposed in (Skukis, 2020).

2.3. The sequence of vibration correlation technique

Based on the information presented in this chapter, the algorithm for taking measurements using the VCT method has been developed.

1. **To determine critical load** $P_{CR,FEM}$ and **the value of the first natural frequency** $f_{P\,=\,0N,FEM}$ using the finite element method. The value of critical load is needed for the VCT-based prediction of the critical load. The value of the first natural frequency acquired using FEM is needed for verification of the computational model with a real tested item, as well as for determination of modal parameters of the experiment.
2. **To determine loading step** depending on the calculated critical load $P_{CR,FEM}$ specified in Chapter 1. The minimum number of steps for the calculation to predict the critical force is 3 qt. $\Delta P = \frac{P_{CR,FEM}}{n}$. My recommendation is to use at least n = 10 qt.
3. To determine **the value of the first natural frequency under loading** $f_{P\,=\,\Delta P}$ using the finite element method.
4. To determine the parameters of the model experiment:
   - **Frequency range**: $0 \cdots 5 \cdot f_{P\,=\,0N,FEM}$
   - **Resolution:** max $\Delta f = \frac{f_{P\,=\,ON,FEM} - f_{P\,=\,\Delta P}}{2}$
   - **Scanning point:** it should be selected so that the overall time of scanning does not exceed 15 minutes or the time set by the commissioner.
5. To take experimental modal measurements without loading. Compare the acquired first natural frequency with the calculated frequency. **Make sure that all measurements correspond to expected ones** and the quality of the acquired shapes of fluctuations is appropriate for use.
6. Two experimental modal measurements under the load equal to Δf, $2\Delta f$ should be taken additionally. This is a mandatory minimum data set to begin the VCT-based prediction of the critical load.
7. To make a VCT-based prediction of the critical load.
8. If the following changes in the loading step do not exceed the calculated critical load $\boldsymbol{P}_{cr}$, then increase the load on ΔP and repeat the measurement, otherwise assume that the critical force has been determined.

A schematic representation of the VCT method algorithm is presented in Fig. 2.19.

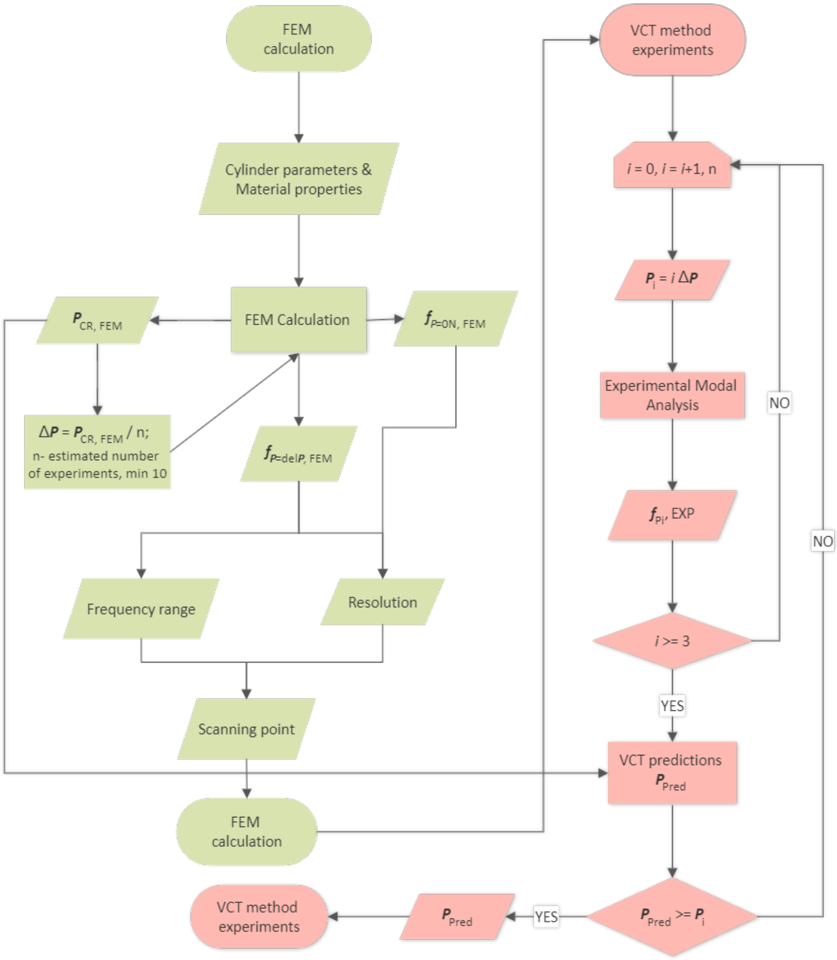


Fig. 2.19. Flowchart of the VCT method.

CHAPTER 3: MAIN RESULTS

Familiarisation and testing for natural frequency decrease under loading in thin-walled cylindrical structures by the vibration correlation technique (VCT) was carried out on two cylinders. A set of cylinders with the diameter of 300 mm and 500 mm was manufactured, they were rolled from ASI 304 0.5 mm thick sheet and then joined by plasma welding. First, the experiment was modelled with the finite element method (FEM) code ANSYS. Modelling VCT with finite elements can be subdivided into two stages. Initially, the calculation is carried out introducing the static load at the axis of the shell and restricting displacements at the other end of the shell. At the second stage, the modal analysis of the shell is carried out by accounting the shell's pre-stressed state from the initial analysis. Next, a physical experiment was carried out. The detailed results are presented in article by *Skukis, E., Kalnins, K., Chate, A. "Preliminary assessment of correlation between vibrations and buckling load of stainless-steel cylinders", Shell Structures: Theory and Applications – Proceedings of the 10th SSTA 2013 Conference, Volume 3, 2014, pp. 325–328, 10th Jubilee Conference on "Shell Structures: Theory and Applications", SSTA 2013, Gdansk, Poland, 16 October 2013.*

The main finding of this paper is the statement that the natural frequency under loading decreases for thin-walled cylindrical structures both in the physical experiment and the finite element method simulation.

The following very important step was to enhance the accuracy of critical force prediction. Analysis of the research in this field shows that the acquired experimental data should be preliminarily normalised. The approach to normalisation suggested by Arbelo is an experimental verification of a novel approach using vibration correlation technique for prediction of realistic buckling loads of unstiffened cylindrical shells loaded under axial compression. Four different test structures were manufactured and loaded up to buckling: two composite laminated cylindrical shells and two stainless steel cylinders. In order to characterise a relationship with the applied load, the first natural frequency of vibration and mode shape is measured during testing using a 3D laser scanner. The proposed vibration correlation technique allows predicting the experimental buckling load with a very good approximation without actually reaching the instability point. The detailed results are presented in article by *Kalnins, K., Arbelo, M. A., Ozolin,s O., Skukis, E., Castro, S. G. P., Degenhardt, R., "Experimental non-destructive test for estimation of buckling load on unstiffened cylindrical shells using vibration correlation technique", Shock and Vibration, Volume 2015, Article ID 729684.*

Based on the experience gained from experiments conducted using the VCT method and the opportunity to produce cylinders similar to those used by other researchers, three identical cylinders were produced and tested. They were normalised using the method suggested by Arbelo. The data acquired within this research are presented in the article by *Arbelo, M. A., Kalnins, K., Ozolins, O., Skukis, E., Castro, S. G. P., Degenhardt, R., "Experimental and numerical estimation of buckling load on unstiffened cylindrical shells using a vibration correlation technique", Thin-Walled Structures, Volume 94, 1 September 2015, pp. 273–279.*

The main finding of this paper is that the first frequency shall be used to ensure the most efficient prediction of the critical force. Further, this statement will be disproved, as there are the frequencies, which disappear during the experiment, those may be also the first frequencies, depending on the geometry and size of a sample. This is why the first frequencies, which remain throughout the VCT testing, should be used.

The normalisation method suggested by Arbelo is not the only one, its comparison with the method suggested by Souza in 1983 is presented in the work by *Skukis, E., Ozolins, O., Andersons, J., Kalnins, K., Arbelo, M. A., "Experimental Test for Estimation of Buckling Load on Unstiffened Cylindrical Shells by Vibration Correlation Technique", Procedia Engineering, Volume 172, 2017, pp. 1023–1030, 12th International Conference Modern Building Materials, Structures and Techniques, MBMST 2016, Vilnius, Lithuania, 26 May 2016*.

This paper also presents optimized boundary conditions for experiments. Optimization excludes the impact of an operator on the final result. Comparison of the impact of boundary conditions is presented in the article by *Skukis, E., Ozolins, O., Andersons, J., Kalnins, K., Arbelo, M. A., "Applicability of the vibration correlation technique for estimation of the buckling load in axial compression of cylindrical isotropic shells with and without circular cutouts", Shock and Vibration, Volume 2017, 29.* The main aims of this paper is to test the opportunities to predict critical force in cylindrical shells with evident defects.

The main finding of this paper is the conclusion that the changed boundary conditions increase the bearing capacity avoiding deterioration of the accuracy in prediction of critical force using the VCT method. This work also represents a simplified and enhanced production process of cylindrical shells by replacing a welded joint for an adhesive bond, which also increases the bearing capacity by 35 %. Furthermore, same as in the earlier works, the most precise prediction is observed within the range close to the critical force. Predictions of the critical force with defects require adjustments and, most likely, another approach to predictions of the critical force.

Application of VCT prediction of the critical force for double load caused by inner pressure and central compression was tested on an orthotropic cylinder. These results are presented in the article by *Franzoni, F., Odermann, F., Wilckens, D., Skuķis, E., Kalniņš, K., Arbelo, M. A., Degenhardt, R. "Assessing the axial buckling load of a pressurised orthotropic cylindrical shell through vibration correlation technique", Thin-Walled Structures, Volume 137, April 2019, pp. 353–366.*

The studies on a more advanced method of VCT test data normalisation are partly discussed in the paper by *Skukis, E., Jekabsons, G., Andersons, J., Ozolins, O., Labans, E., Kalnins, K. "Robustness of empirical vibration correlation techniques for predicting the instability of unstiffened cylindrical composite shells in axial compression", Polymers, Volume 12, Issue 12, December 2020.* This work compares two normalisation techniques: the one suggested by Arbelo and the other developed by RTU.

During the work supported by the grant from the Latvian Council of Science, grant number LZP-2018/2-363, a web-site http://vct.rtu.lv/ was designed to report about all testing procedures, the technique and the equipment, as well as the test results for 59 cylinders. All cylinders were produced of a composite material in three diameters – 100, 300, 500 mm, with various heights from 150 mm to 750 mm and two kinds of layering optimised for the maximum bearing capacity with 3 and 4 layers, respectively. The data are available at *http://vct.rtu.lv/*.

A review of the critical force prediction using the VCT method is presented in the work by *Skukis, E., Kalnins, K., Jekabsons, G., Ozolins, O., "Benchmarking of vibration correlation techniques for prediction of buckling load of cylindrical shells", 16th European Conference on Spacecraft Structures, Materials and Environmental Testing (ECSSMET), 2021.*

The process of the implementation of the VCT method is described in Fig. 3.1.

Fig. 3.1. The main results of the implementation of the VCT method presented in the publications.

CHAPTER 4: FINAL REMARKS

In this final chapter, the main achievements of the Thesis are discussed in Section 4.1, whereas Section 4.2 provides critical recommendations and Section 4.3 gives a perspective for future research.

The main work in the presented dissertation can be summarized as follows:

1. As a first step correlation between increment of load level and decrease of frequency has been experimentally confirmed for cylindrical shells. This proof of hypothesis enabled us to further study the applicability of the VCT method for cylinders with and without damage. Nevertheless, initial trials also outlined findings that eigen frequencies do not tend to be equal to 0 Hz upon reaching the buckling load level, which requires a redefinition of criteria or new solutions for normalisation of correlation assumptions.
2. In the present research, a total of 76 cylinders were produced and experimentally tested using the VCT method. Out of particular test campaigns 17 specimens were isotropic while 59 specimens were orthotropic. The dimensional ranges covered R/t ratio 100…2000, given minimum cylinder diameter is 100 mm, the maximum is 8000 mm. Similarly, experimentally assessed series ranges for R/h = (1/1 to 1/4). Minimum height is 200 mm, maximum 6000 m.
3. Five different testing equipment and set-ups have been assessed including electromagnetic and hydraulic testing jigs as well as axial compression, axial & bending and axial & internal pressure setups. These test series cover four testing laboratories: RTU Institute of Materials and Structures, Forest and Wood Products Research and Development Institute in Jelgava, DLR Institute of Composite Structures and Adaptive Systems in Braunshweig –, and IMA Materialforschung und Anwendungstechnik GmbH in Dresden.
4. Approbation of the VCT method has been demonstrated on a real scale object – the cryogen tank of the Ariane-6, the newest generation European launcher during its certification testing campaign. Two separate load cases have been investigated and VCT applicability approved. Full-scale tests have confirmed requirements and settings for frequency measurement resolution, location of measurement equipment and ability for seamless integration in certification procedures for full-scale structural tests.
5. As a benchmark both ANSYS and ABAQUS commercial finite element code parametric models have been developed and correlated providing an open source code for the research community as a validated benchmark example on an open data web portal https://vct.rtu.lv/ansys.html. Numerous boundary conditions, multilayer stacking sequence combinations and material models are made available and tested.
6. It has been confirmed that testing with hydraulic force actuators should be done with diligence, as equipment excites a phantom frequency which does not diminish throughout load level increment. Therefore, it is very important to isolate the source of vibration.

4.1 Main conclusions

1. It has been confirmed that a classical approach leading buckling/self-frequency correlation to 0 Hz is not valid for composite cylindrical shells. A new normalisation approach for VCT prediction originally has been applied and approached by Souze in 1983. An experimental work has led to contribution of normalisation method also referred as Arbelo (2014) and further improvement Skukis (2020) of developed method based on statistical dataset approbated during the presented research work.

2. It was found that the prediction accuracy of the buckling load using either VCT approach proposed by Arbelo or its empirical modification approach proposed by Skukis was virtually insensitive to shell geometry and mounting and loading methods. Moreover, the VCT methods also appeared robust with respect to a lack of natural frequency data for an unloaded shell caused, e.g., by the need for a preload to reliably fix the shell in the test rig. Both VCT methods tended to slightly underestimate the critical load for shells with relatively large experimental KDF values, thus providing not only close but also conservative estimates of the limit load for high-quality shells.

3. The modified VCT has been demonstrated to be an efficient tool for nondestructive prediction of the load-carrying capacity of intact shells. The discrepancy of the predicted and experimental critical load of less than about 10 % was attained when the reduction of fundamental frequency of a shell was monitored under axial loads in excess of 60 % of the buckling load. By contrast, appearance of a local buckling at the cutout, preceding the global buckling of a shell, was found to invalidate the considered VCT for shells with holes.

4.2 Critical recommendations

A testing guidance has been formulated for scaling up vibration correlation technique drawing several critical recommendations:

- A batch of several frequencies should be analysed simultaneously during the load application process by monitoring overall frequency shift estimating statistically proved dependency.
- The best structural excitation and frequency response capture for cylindrical structures could be realised by loudspeaker localization avoiding contact with the testing surface. This reduces both added mass and contact induced frequency mode shape divergence compared to other means of excitation.
- A laser scanning is the best suited method for non-contact frequency and is both scalable and time sensitive during a testing campaign.
- A zero-load level should not be considered, as frequency response may vary compared to actual load distribution pattern. Therefore, a load level of 5 % of linear buckling load should be considered as a first reference point for estimation of VCT.

- Satistical indicators, e.g., modal assurance criteria or modified modal assurance criteria, are a must in monitoring of response in order to clear out structural ghost frequencies from testing grounds or dissipating and merging of frequencies.
- A way to visualise experimental progress has been proposed by plotting frequencies versus oscillation amplitude intensity, therefore providing a comprehensive overview of test campaigns progress.

4.3 Further outlook

Several aspects have been identified for further extension of current research:

- The obtained experimental data set should be further elaborated in development of a frequency shift method including application of machine learning processes for VCT method, thus determining the unloaded waveforms, the safest state for the design and the optimal points for scanning of structural frequencies. It has to be done in order to speed up and simplify the testing process and at the same time to increase the prediction accuracy.
- For a practical applicability, a dedicated (vibration sensor + GSM or WiFi module) IoT sensor can be developed for monitoring a set critical frequency shift and for structural health monitoring.

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