Chapter 12
Experimental Modal Analysis of a Twin-disc Tribometer using a 3D-scanning Laser Doppler Vibrometer

A. Mario Puhwein, Andreas Biederbeck, Balazs Jakab, Markus Varga, and Markus J. Hochrainer

Abstract Tribometers are employed to analyse the friction and wear properties of material pairings. A twin-disc tribometer enables the dynamic analysis of disc pairs. The dynamic behaviour of the testing machine can significantly influence the tribological results. To quantify these influences and precisely model the systems, the dynamic parameters of the test stands, must be precisely determined. The latest measuring technologies, such as 3D scanning laser Doppler vibrometers, are employed for this purpose. One of the key advantages of this technology is its ability to perform non-contact measurements on rotating components, which enables high-resolution and precise recording of the vibrations. Another advantage of this innovative technology is, that it allows the detection of complex displacements and vibration modes in three dimensions, which leads to significantly improved modal parameters. The primary objective of this study is to identify the modal parameters of a twin-disc tribometer through experimental and numerical modal analysis. These findings provide the foundation for the development of a digital twin test rig. It enables a more precise prediction of the tribometer's behaviour under different operating conditions, thus contributing to optimisation of tribological tests and improvement of material pairings. The utilisation of such sophisticated measurement system and analytical techniques represents a significant advancement in tribology, thereby facilitating the development of more efficient and durable materials.

Keywords 3D-scanning laser Doppler vibrometer · Twin-disc tribometer · Experimental modal analysis · Tribology

Introduction

A twin-disc tribometer is a specialized testing apparatus used in tribological research and material testing to study friction and wear between two rotating surfaces. This device enables realistic simulations of the contact conditions encountered in many engineering applications, such as in the automotive industry, mechanical engineering, and materials science. The basic operation of a twin-disc tribometer involves two discs, which can be made from same or different materials, rolling or roll-sliding contact against each other while various parameters such as pressure, speed, and temperature are controlled. [1]

An important application of the twin-disc tribometer is in researching wheel-rail contact, particularly in the study of railway vehicles. In this context, the slip ratio can be varied to simulate the interaction between the wheel and rail under different operating conditions. These tests are crucial for understanding phenomena like corrugation and general rail surface wear, which directly impact the safety and efficiency of rail transport [2]. Moreover, the twin-disc tribometer is frequently used in the automotive industry to test the friction properties of brake pads and discs. These tests are essential for evaluating the performance and durability of brake components. By analysing friction under various conditions, such as different temperatures and pressure levels, engineers can optimize material composition and treatment to ensure improved braking performance [3].

In the mechanical engineering sector, the twin-disc tribometer plays an important role in examining the fatigue behaviour of transmission components. This test method is used to analyse the dynamic properties and their behaviour under repeated

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loads. These insights are particularly important for the development of durable and reliable drive systems, used in a wide range of applications, from vehicles to industrial machinery [4]. Another example of the twin-disc tribometer applications is the study of wear mechanisms in polymer materials [5]. When developing new plastics, it is important to understand how these materials behave under different contact conditions. The twin-disc tribometer allows for testing specific properties such as wear resistance and temperature stability, thereby facilitating the selection of suitable materials for various applications.

A key advantage of the twin-disc tribometer is its ability to provide precise and reproducible measurements. By continuously monitoring parameters such as torque, speed, and temperature, researchers can gain a detailed understanding of the tribological processes occurring in the contact area. These data are essential for predicting material behaviour in real-world applications and for developing effective strategies to minimize wear.

However, it is important to note that the twin-disc tribometer exhibits eigen-dynamics that must be considered. These dynamics refer to the internal vibrations and movements of the system that can occur during testing. To accurately assess the influence of the device's dynamic behaviour on the tribological results and reduce their impact, the dynamic behaviour of the tribometer must be thoroughly understood and described. A comprehensive analysis of these aspects can help minimize systematic errors and improve the validity of the test results. [6]

In summary, the twin-disc tribometer is an indispensable tool in tribological research. With its wide range of applications across various industries, it contributes to a deeper understanding of friction and wear, supports the development of new materials, and improves the efficiency of technical systems. The ongoing development of these testing methods and technologies will continue to play a central role in materials research and testing, helping to meet the challenges of the future industrial demands.

In this context, the development of a digital twin of such a tribometer is becoming increasingly important. A digital twin enables the virtual simulation of real test conditions, allowing for the analysis of system behaviour under various conditions without the need for extensive physical testing. This not only saves time and costs but also opens up new possibilities for optimizing materials and systems. [7]

However, to develop a digital twin, a highly precise and well-calibrated simulation model is essential. Only such a model can accurately replicate the complex dynamic and tribological processes of the real tribometer and provide reliable predictions. Precise calibration of the model using experimental data is critical to ensuring alignment between simulation and reality, thereby unlocking the full potential of the digital twin. [8]

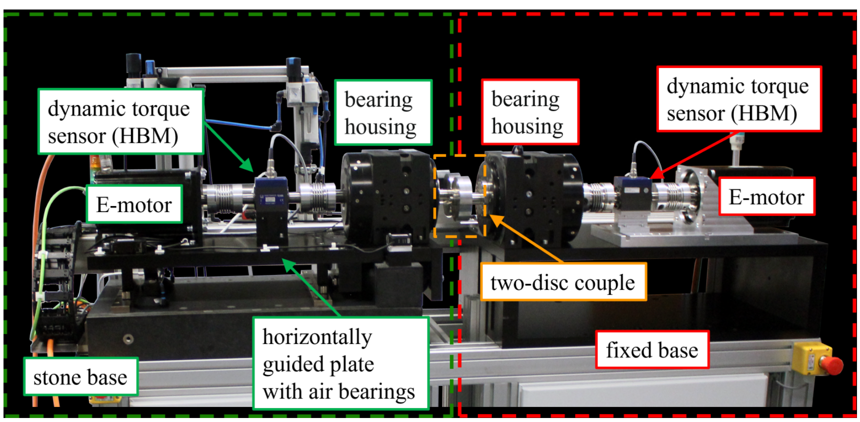


Fig. 1 Twin-disc tribometer and its main components to be analysed

The aim of this work is to investigate the eigen-dynamics of the twin-disc tribometer [3], with particular emphasis on certain components of this test apparatus, as illustrated in Fig. 1. The discs are mounted on two parallel drive trains, each powered by BHM1403P06A2A E-motors (Schneider Electric, Austria) with a nominal torque of $14.4\ Nm$. The speed of the two discs can be controlled continuously and independently of each other, allowing for small slip ratios from $< 1\%$ up to 100%, at rotational speeds from 0 to 1500 rpm. To minimize internal friction, the moving side is supported in the horizontal plane with air bearings EZ-0053-080 (Eitzenberger, Germany). The load is applied by a pneumatic cylinder, ensuring that the moving side can be pressed horizontally against the fixed side in the horizontal plane. The acting normal force is measured by a force transducer C9C (Hottinger Brüel & Kjaer, Germany) The coefficient of friction is determined via the torque, which is measured in both drive trains using a torque sensor T21WN (Hottinger Brüel & Kjaer, Germany).

In order to accurately investigate the effect of the eigen-dynamics of the twin-disc tribometer on the tribological results, Experimental Modal Analysis (EMA) [9] is used to analyse the vibration behaviour and identify the modal parameter of the system. This method allows a detailed capture and understanding of the system's natural modes of vibration. Advanced technologies such as laser Doppler vibrometers (LDV) [10] are used in combination with an automated modal hammer. This setup allows for precise measurement of the vibration modes of the tribometer.

The collected data are then analysed using AbraVibe [11] in MATLAB©, which allows the determination of various modal parameters. These parameters include effective mass, damping, stiffness, eigenvalues, and eigenvectors. Such modal parameters are critical for understanding the dynamic properties of the system and for identifying potential weaknesses and unwanted resonances that could affect the quality of tribological test results.

With EMA, engineers and researchers can capture the natural frequencies of the mechanical system and take targeted action to mitigate the effects of its eigen-dynamics. This not only improves the accuracy and reproducibility of measurement results, but also helps to improve the reliability and performance of the entire test setup. Another key benefit of these approaches is their potential to promote environmentally friendly, climate-neutral, and resource-efficient solutions. By increasing the efficiency of materials and processes, both material consumption and environmental impact can be reduced. These analyses are essential to ensure the quality of tribological research and to develop innovative materials and technologies that meet the demands of modern applications.

Methodology

In this work, LDVs are mainly used to record measurement data, offering the advantage that they do not need to be physically connected to the structure due to the non-contact measurement process and therefore do not influence the dynamic behaviour of the system [12].

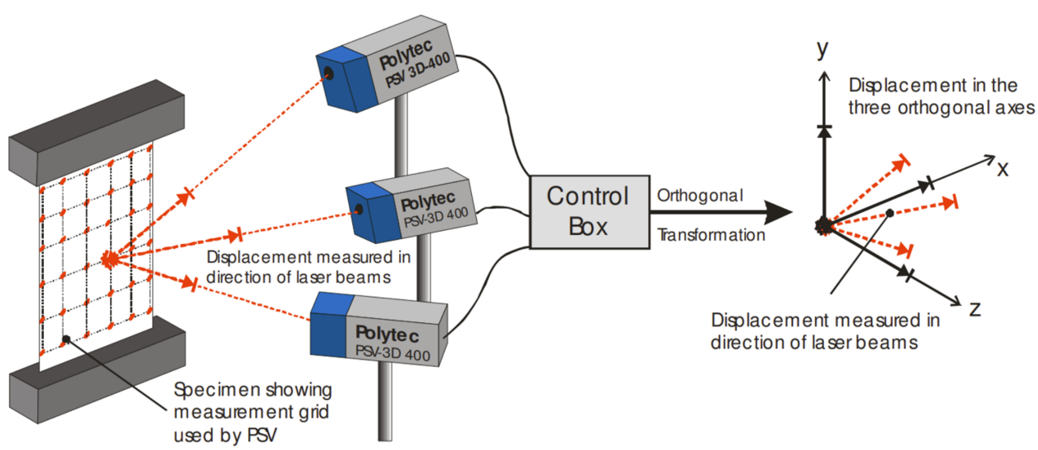


Fig. 2 Schematic of the vibration measurement with the 3D scanning LDV and the determination of the Cartesian components from the 3 laser measurements [13]

LDVs operate on the principle of the Doppler effect, allowing them to directly and accurately measure surface velocity by detecting the frequency shift between the incoming and reflected light received by the measurement system. Similar to a 3-axis accelerometer, multiple LDVs can be used to measure three-dimensional displacement by arranging three scanning LDVs in a specific configuration. When properly aligned, LDVs provide measurement data comparable to that of commonly used accelerometers [9]. Fig. 2 schematically illustrates the operation of a 3D scanning LDV, showing how the vector sum of the three individual laser heads produces a result that can be easily transformed into the three components of a cartesian coordinate system. This capability proves to be a significant advantage when interpreting vibration modes in practice [14]. Thanks to the scanning function of LDVs, it is possible to quickly acquire large amounts of data from extensive structures and analyse large structures with a high density of measurement points [15].

In this study, classical EMA is used to identify the modal parameters of the mechanical system. EMA uses known or specially generated excitation forces (modal hammer, shaker) and the resulting accelerations, velocities or displacements to analyse the dynamic behaviour. To perform a modal analysis, measurement data are first obtained and frequency response functions $H(\omega) = V(\omega)/F(\omega)$ where V, F, ω represent the frequency spectrum of the measured velocity, the excitation force, and the excitation frequency, respectively. Following this, more general system identification methods are applied to determine the modal parameters of the studied model.

From these transfer functions, the modal parameters can be extracted using the following polynomial approach:

$$H(\omega) = \sum_{r=1}^{N} \frac{\phi_r \, \phi_r^T}{\zeta_r \omega_r + j\,(\omega - \omega_{d,r})} + \frac{\phi_r^* \, (\phi_r^*)^T}{\zeta_r \omega_r - j\,(\omega - \omega_{d,r})} \tag{1}$$

where ϕ_r and ϕ_r^* represent the eigenvector and its complex conjugate, ζ_r is the damping ratio, ω_r the undamped natural frequency, $\omega_{d,r} = \omega_r \sqrt{1-\zeta_r^2}$ the damped natural frequency of the r-th mode of the system, ω is the excitation frequency, and N represents the number of modes. [9]

As the modal order (N) is increased, there is a systematic expansion of the model framework which is compared with the measured transfer function. This comparative analysis includes an assessment of the stability of the pole pairs with respect to selected parameters such as eigenfrequencies and damping ratios. The results of these stability investigations are presented in stability diagrams, from which the stably identified modes and their modal parameters can be derived. [11]

Another essential instrument in the EMA is the Modal Assurance Criterion (MAC) matrix, which is used to assess the similarity between mode shapes obtained from the same or different measurements or to compare measurement results with numerical simulations. The MAC between two mode shapes ϕ_r and ϕ_s is defined as:

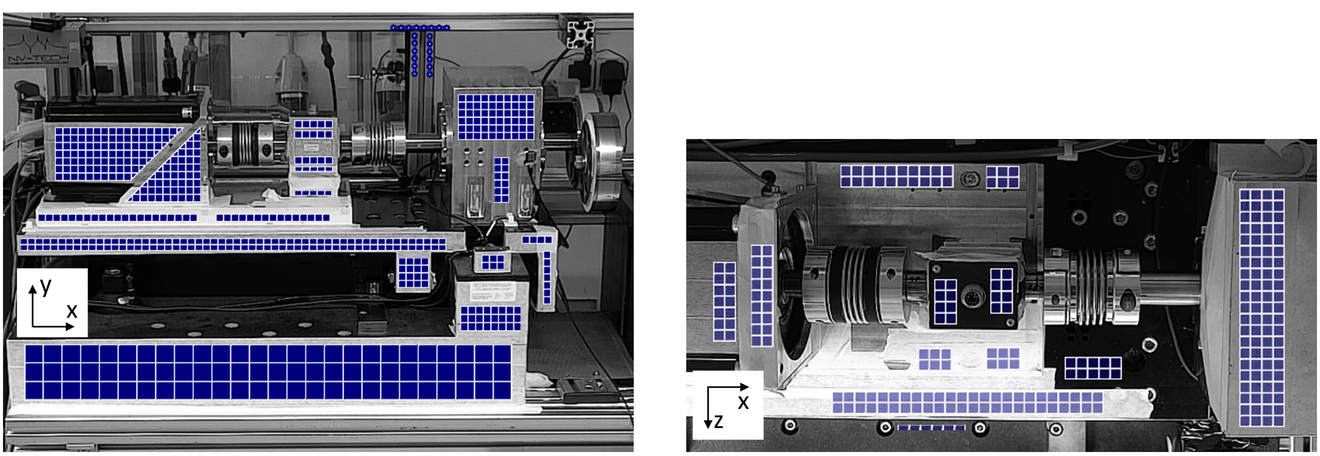
$$\mathrm{MAC}_{r,s} = \frac{|\phi_r \, \phi_s|^2}{(\phi_r^H \phi_r)\,(\phi_s^H \phi_s)} \tag{2}$$

where ϕ_r and ϕ_s and ϕ_r^H and ϕ_s^H are the r-th and s-th modes and their Hermitian transposes.

The MAC values range is between 0 and 1, with a MAC value of 1 indicating that the mode shapes are identical, while a value of 0 means that they are orthogonal. Values between 0 and 1 indicate partial similarity. To determine the MAC for a system with several mode shapes, a MAC matrix is created in which the MAC values for all possible pairs of mode shapes are mapped. Dependencies between modes in one measurement or different measurements can be determined. Furthermore, the matrix is crucial for the validation of experiments and numerical models, as high MAC values indicate successful modelling of the dynamic properties of a system. Thus, the MAC is an important tool in dynamic analysis that contributes to the quality assurance of models and is essential for the development of digital twins. [9]

Measurement Setup

In order to facilitate the detection of the various vibration modes, the test stand is subjected to measurements from two distinct directions: from the "front" and from the "top." The front measurement direction is chosen to capture movements mainly in the x- and y-axes of the components, while the top measurement direction allows movements in the z-x plane to be recorded, focusing on the torsional modes of the horizontally mounted plate on the flexible side of the test rig. The measurement grids used are shown in Fig. 3. Excitation by a modal hammer was mainly applied to the two discs to stimulate the modes that would also be excited by frictional contact during the operation of the test rig.



(a) (b)

Fig. 3 Measurement grids on the twin-disc tribometer a) "front" direction b) "top" direction

For the measurements, a steel disc with a diameter of 145 mm and a width of 40 mm was mounted on the rigid side, while a steel disc with a diameter of 140 mm, a width of 40 mm and a composite layer of approximately 5 mm thickness and 30 mm width was used on the flexible side. These discs were pressed together with a normal force of 800 N.

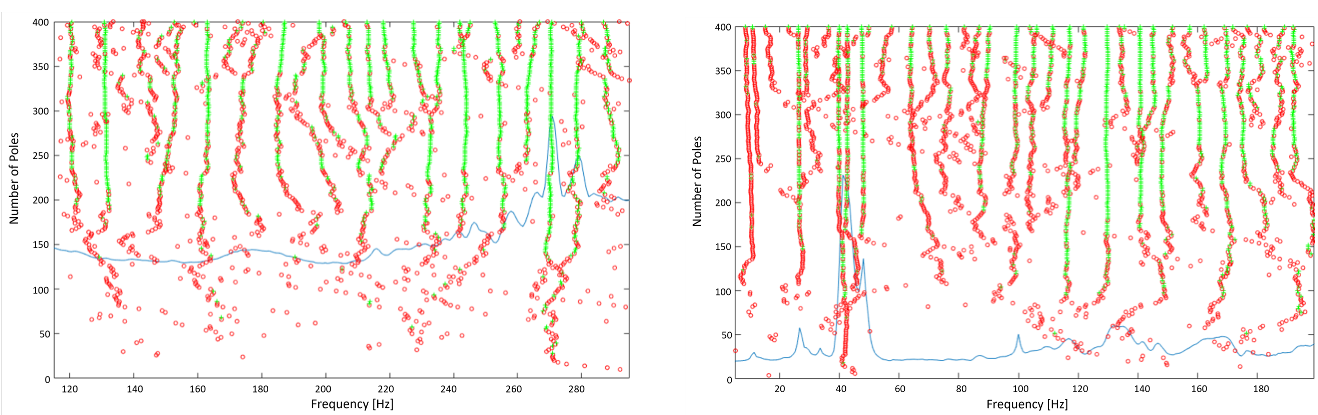
Advanced measuring instruments were used to perform the modal experiments and collect data, including a SAM1, a scalable modal hammer (NV-Tech, Germany), high-precision HBK 4524 and HBK 4507-B accelerometers (Hottinger Brüel & Kjaer, Germany), and state-of-the-art 1D and 3D laser Doppler vibrometers (LDV), including the VibroGo and the 3D scanning laser Doppler vibrometer PSV-3D QTec-600 (Polytec, Germany) [16].

The measurements were conducted for all scanning points with a bandwidth of 12.8 kHz, a sampling rate of 32 kHz, a measurement time of 4 s, and a frequency resolution of 0.25 Hz. A complex averaging over three repetitions was applied, and the calibration factor was set to 25 mm/s. Velocities and accelerations were measured using an exponential window, while force was measured with a force window. Speckle tracking was set to “very good,” and the tracking filter was configured to “slow.”

Results

This chapter presents the results of the experimental modal analysis of the two-disc tribometer. The measurement data described in the previous chapter are analysed to identify the different vibration modes and their associated modal parameters. The data recorded with the PSV-3D QTec-600 are analysed using the AbraVibe toolbox in MATLAB [11], as mentioned before, to investigate the relationships between the excitation frequencies and the resulting natural frequencies of the system and to describe the dynamic behaviour of the tribometer. It is important to note that the presented results represent only a very small excerpt of the entire measurement campaign, which was extensive in scope.

As discussed in the Methodology chapter, the results of the parameter identification are visualised in stability diagrams (see Fig. 4 to provide a clear understanding of the identified modal properties. In these diagrams, the frequency is plotted on the x-axis and the number of poles on the y-axis (see equation 1). The red ‘o’ indicates unstable pole pairs and the green ‘+’ stable pole pairs. For better visualisation, the transfer function used for identification (blue line) is also shown. Fig. 4a) shows four identified modes in the frequency range from 240 Hz to 290 Hz, which are labelled with green ‘+’ at the upper end of the y-axis. These were detected by the measurements from the “front” direction. Furthermore, the stability diagram in Fig. 4b) shows a stably identified vibration torsion mode at 140 Hz, which was recorded from the “top” direction.

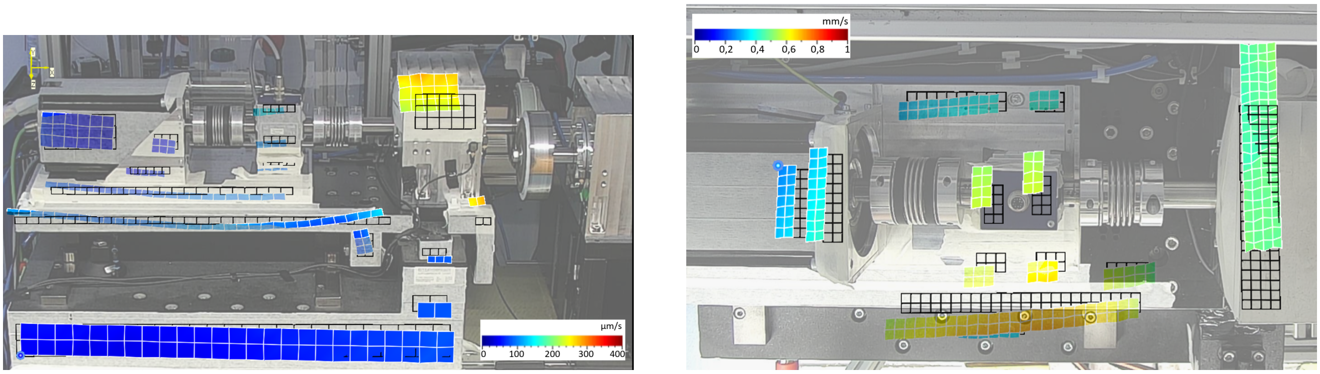


(a) (b)

Fig. 4 Stability diagrams of the identification process for one measurement result in the a) ‘front’ direction b) ‘top’ direction

In the 3D representation of the vibration modes, the various vibration modes of the tribometer are visualised to illustrate their spatial distribution and intensity. These visualisations provide a clear insight into the dynamic properties of the system and show how the individual components behave in different frequency ranges. The 3D animations help to recognise relevant vibration modes such as torsional modes, bending modes and others that can occur during operation. This makes it possible to better understand and analyse the behaviour of the tribometer under realistic operating conditions.

Fig. 5 a) shows a mode shape at $270,4$ Hz with a damping ratio $0,56\%$. It can be observed that the stone slab foundation moves up and down on the right-hand side, while the flexible slab mounted on it with air bearings shows a bending mode. In addition, the movements of the attachments on this plate indicate a bending mode, as the motor moves up and down with its

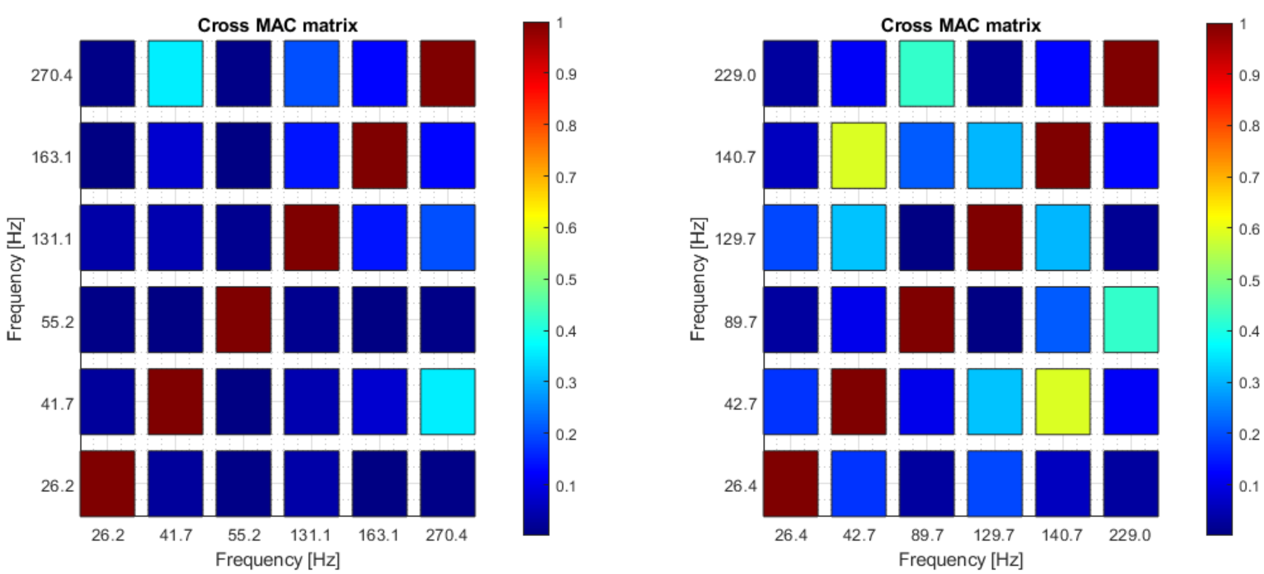


(a) (b)

Fig. 5 Visual representations of mode shapes at a) $270,4\ Hz$ form “front” direction b) $140,7\ Hz$ from “top” direction

free end. The bearing housing on the right-hand side also shows a rotational movement around its mounting. Fig. 5b) shows a mode shape at $140,7\ Hz$ with a damping ratio $0,92\%$. The 3D animation clearly shows that the flexible plate exhibits a torsional mode. This is clarified by the movement of the attachment parts, in particular by the counter-movements of the bearing housing and the motor. In both the “front” and “top” measurements, the discs with the composite cover are excited by an impact from the automatic modal hammer onto the support steel disc.

Fig. 6 presents the MAC matrices (see equation 2) determined for the measurements shown in Fig. 4 and 5, comparing the modes of the respective measurements. The matrix in Fig. 6a) shows the results of the “front” direction measurement, where it can be observed that the modes at $41.7\ Hz$ and $270.4\ Hz$ exhibit a similarity of approximately 40%. This can be attributed to the tilting motion of the bearing housing around the plate in both modes. In the “top” direction measurement, mode similarities are also present, which were confirmed through detailed analyses of the mode animations. Notably, the modes at $42.7\ Hz$ and $140.7\ Hz$, as well as at $89.7\ Hz$ and $229.0\ Hz$, show a similarity of 55% and 45%. These similarities were again traced back to the pronounced movements of the bearing housing.



(a) (b)

Fig. 6 MAC matrix for the respective measurement to compare the modes with one another for a) ‘front’ direction b) ‘top’ direction

Conclusion

In this thesis, experimental modal analysis was successfully performed on a two-disc tribometer using a 3D scanning laser Doppler vibrometer. The modal parameters of the system were precisely determined in order to better understand the natural dynamic behaviour of the test bench. The non-contact measurement method of the LDV proved to be advantageous, as it enabled the precise recording of the vibration modes without influencing the system itself.

The results obtained provide important information about the natural frequencies, damping rates and mode shapes of the tribometer. This represents an essential step in the development of a realistic simulation model (virtual prototype), which forms the basis for the creation of a successful digital twin [17]. Such a digital twin allows the accurate simulation of the real behaviour of the test rig under different operating conditions and thus contributes to the continuous monitoring and prediction as well as the optimisation of tribological tests.

The experimental identification of the dynamic properties allows the simulation model to be precisely calibrated [18], which is a significant aspect for the further development of a digital twin. Understanding the natural dynamics of the test bench is also an essential step in being able to correctly interpret the frequency-dependent tribological results. These results are an important contribution to improving the predictive accuracy and reproducibility of tribological tests and support the further development of tribological measuring devices, material pairings and lubricants.

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