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TAXI VIBRATION TESTING: A NEW AND TIME EFFICIENT PROCEDURE FOR THE IDENTIFICATION OF MODAL PARAMETERS ON AIRCRAFTS

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Abstract:

In order for aircraft prototypes to perform first flight, a flutter clearance to guarantee aeroelastic stability has a fundamental role in the required certification process. The Ground Vibration Test (GVT) is the standard means to determine the dynamic characteristics of the structure which are subsequently used to update numerical models for the flutter clearance. The GVT must be performed at a time critical phase of an aircraft's development and has therefore been significantly improved and optimized over the last 20 years. In order to achieve further reduction of testing time a completely new philosophy for testing was needed. This resulted in the Taxi Vibration Test (TVT) which uses advanced methods to process output-only data during aircraft taxi to identify modal parameters. The method was developed at DLR Göttingen and has gone through a process of maturation including model and full scale investigations. In this work the final maturation of the method as a viable alternative for efficient certification is demonstrated on data from the A340-600 Research GVT performed in cooperation with Airbus and ONERA in the year 2011. A comprehensive set of modal parameters were identified using the Stochastic Subspace Identification (SSI) method. The influence of the measurement duration on the uncertainty of the modal parameters was investigated statistically. In a TVT, the landing gears are involved in the vibration. These are known to be non-linear, mainly because of the slip-stick type of friction non-linearity in the shock absorbers. Therefore, the importance of the relationship between the taxi speed, which is related to the unknown excitation force, and the modal parameters was identified. The modal acceleration spectra were used as a proxy to quantify this non-linearity in order to provide a meaning comparison between GVT and TVT. Trends of decreasing frequency and increasing damping with increasing speed were observed, which is in agreement with friction type non-linearity. The influence of the landing gear to increase damping and reduce frequency of specific modes was also identified and discussed. The comparison between GVT and TVT confirm this force dependency of the modal parameters. The modal parameters identified from SSI show significantly improved damping estimates and trends, increasing the confidence in the TVT method as a viable alternative for optimal aircraft certification.

1 INTRODUCTION

In the certification process of aircraft prototypes a Ground Vibration Test (GVT) is required by the airworthiness authorities to determine the dynamic characteristics of the structure in terms of eigenfrequencies, mode shapes and damping ratios. The experimental modal parameters are used in the flutter clearance process to update numerical models, which are then used to determine the aeroelastic stability within the flight envelope.

The classical GVT is performed under high pressure just before first flight. During this kind of test the aircraft is placed inside a hangar while it is excited by electro-dynamic shakers installed at numerous positions enabling linear independent excitation configurations. For shaker placement, especially designed platforms for optimal force injection are employed. Due to the size and complexity of the aircraft structure, it needs to be excited using various combinations of different excitation positions to identify the modal parameters in the frequency range of interest. In most cases, correlated multi-point excitation is being used in terms of swept-sine excitation with low sweep rates. The aircraft symmetry and anti-symmetry behaviour is exploited for establishing excitation configurations. Since the aircraft will be operated in different configurations, due to changes in fuel during flight and different cargo and passenger setups, it also needs to be tested in different structural configurations. Finally, a well-trained testing team is essential for high quality data acquisition, data processing, and data analysis. These requirements result in large time demands during a test campaign.

Throughout the whole test phase the structure has limited accessible for other working parties. This fact is very unsatisfying for the aircraft manufacturer who frequently asks for shorter test duration. Within the last 20 years the GVT methods have been improved significantly leading to a significant reduction in testing time. Nevertheless the potential for further significant reduction of testing time by optimization of the individual tasks in classical GVT is hard to achieve. Therefore a completely new philosophy for the identification of modal parameters needs to be applied if further reduction of testing time should be achieved.

1.1 Taxi Vibration Testing (TVT)

The Institute of Aeroelasticity of the German Aerospace Center (DLR) in Göttingen developed the Taxi Vibration Test (TVT) method for the identification of the dynamic characteristics of aircraft structures [1-3]. A comprehensive description was published in [4]. Important observations relating to this work will be summarized below. This technique makes use of Output-Only Modal Analysis (OMA) where only the acceleration responses during aircraft taxiing are necessary for the modal parameter identification. The idea was first investigated in 2006 on a laboratory structure named AIRMOD (AIRcraft MODel) shown in Figure 1. AIRMOD is a replica of the well-known bench mark GARTEUR structure SM-AG19 and has been studied in detail by Govers [5]. For TVT the structure was placed on a conveyor belt with artificial bumps. The main research objective was to determine whether a complete set of modes could be identified as compared to a regular GVT.

Figure 1: AIRMOD with landing gear on a conveyor belt to investigate the TVT approach for the first time (left). Taxi vibration test on Do228 commuter class aircraft in Brunswick, Germany (right).

A comprehensive mode set was identified during TVT compared to GVT by Böswald et al. [3]. In total 29 modes could be identified during TVT using the Frequency-Spatial Domain Decomposition (FDD) technique with 32 modes during GVT using the Polyreference Least Squares Complex Frequency domain (PolyMAX) method in the frequency range from 5 Hz to 360 Hz. The frequencies and mode shapes showed high correlation with a mean frequency deviation of 0.6 % and an average MAC of 91 %. The damping estimates were however inconsistent with a mean damping deviation of 76 % identified during TVT. Nevertheless, the investigation successfully demonstrated the potential of the new TVT method, and was the catalyst for extending the method to real aircraft and improving the quality of the identification results.

A mathematical model of an aircraft rolling on a rough track was then formulated to investigate the effects of driving speed, fuel configuration and artificial bump height and distance on the modal parameters [4]. A main finding was that the equivalent frequency of excitation was a function of the driving speed, and that the higher the driving speed the higher equivalent frequency excited. It was however also observed that the cost of a broader excitation spectrum was lower magnitudes of excitation at lower frequencies, which could result in weakly excited modes. Finding the optimal trade off point between the number and quality of identified modes and the towing speed is still an open topic for future research.

The first TVT on a commuter aircraft was subsequently conducted on the DLR research aircraft Dornier Do 228, shown in Figure 1, in 2008 in Germany. The measurement setup consisted of 80 accelerometers, and the test was performed with different driving speeds on a flat runway, bumpy runway and specially prepared track with wooden obstacles. A total of 23 modes were identified from TVT using the operational Least Squares Complex Frequency (LSCF) algorithm compared to 28 modes from the conventional GVT performed on the same configuration [1]. Despite the successful identification of a large modal model during TVT, a systematic deviation as compared to the GVT results was observed for the first time. The reason was explained to be a result of the dynamic behavior of the landing gear. During GVT the shaker excitation was not sufficient to drive the landing gear out of sticking friction, however during TVT the landing gear was observed most commonly in sliding friction. The result as explained by Böswald and Govers, is a non-linear effect which is dependent on the displacement amplitude of the shock absorbers resulting in lower stiffness and increased damping of the structural system at low frequencies. The effect of the measurement duration of 600 s was also identified as an important parameter for further investigation.

Building on the lessons learned, the TVT method was extended to a short range large transport aircraft, the DLR research aircraft ATRA A320-200 shown in Figure 2, in a joint Airbus-DLR campaign in 2009. The measurement setup consisted of 138 acceleration sensors, deflection sensors on the landing gear, and aircraft operational parameters such as speed over ground, engine speed, control surface angular deflection, temperature, fuel capacity, aircraft center of gravity etc. The effects of various towing speeds and runway surfaces as well as longer measurement durations were again investigated. After correlation of the results 38 modes were identified from TVT using operational LSCF compared to 46 modes from GVT using PolyMAX in the frequency range up to 35 Hz. Several important observation were made by Böswald and Govers[4, 6]: 1. The TVT vs GVT MAC comparison showed high correlation with the exception of the landing gear modes which were not identified during GVT, and fewer modes over 25 Hz during TVT due to limited excitation amplitude in this band. 2. When focusing on the frequency range up to 15 Hz, which is most relevant for FE model updating of large transport aircraft, there were only two modes from the GVT that could not be identified from TVT. 3. Good repeatability was confirmed for TVT. Furthermore it was concluded that measurement duration played a significant role in the quality of the modal model. It was also concluded that the prepared vs unprepared track did not significantly influence the results.

Figure 2: Taxi Vibration Test on the DLR research aircraft ATRA, an A320-200 (left). TVT on HALO on the DLR premises in Oberpfaffenhofen (right).

The TVT was further demonstrated as an efficient method for certification of the DLR research aircraft HALO, Gulftream G550 shown in Figure 2, with modifications to carry scientific instrumentation under the wings. The TVT resulted in reduced certification time for the modification to the aircraft and also served as an important pre-test and functionality check for the Flight Vibration Test (FVT)[7].

1.2 Output-Only Modal Analysis (OMA) and Stochastic Subspace Identification (SSI)

Since it is not possible to measure the input forces during TVT the method relies on Output-only Modal Analysis (OMA). OMA has shown increasing potential in recent years to accurately identify the modal parameters of large structures in actual operating conditions. This is largely due to advances in identification algorithms and signal processing techniques, combined with improved sensor networks and computing power available for processing large sets of data. OMA is based on the use of ambient excitation from actual operation which makes it ideal for TVT as well as flight testing. While several algorithms exist for identifying the modal parameters in time or frequency domain, the superior performance of the Stochastic Subspace Identification (SSI) method particularly regarding damping estimates [8] have made it a key focus to bridge the final gap between GVT and TVT for aircraft certification. The mathematical formulation of SSI can be found in [9, 10] with insights into the implementation and parametric study in [11].

1.3 Main Objectives

In past research activities and systematic studies have been conducted to assess the conditions under which the TVT method yields best performance in terms of results accuracy versus testing time. In contrast to classical GVT the excitation of the structure is unknown in a TVT and the control of the excitation levels is limited, i.e. variation of speed, mass distribution or even additional control surface rotations. As a consequence, the modal excitation levels will show more dispersion and variation in a TVT compared to a classical GVT. While the past emphasis of the research was focussed on the amount of modal parameters identified in TVT, it has changed with rising Technology Readiness Level (TRL) toward reduction of uncertainty in the identified modal parameters and also quantification of the excitation force amplitudes and the contribution of landing gears.

With a switch from commercial tools for operational modal analysis towards in-house developed software code, it became possible to benchmark different modal parameter estimators and to assess meaningful settings of digital signal processing and modal parameter estimation to provide best-practice recommendations enabling successful TVT and to push the results quality further towards the classical GVT.

This paper presents a detailed investigation of the capabilities of the TVT to deliver modal parameters for the purpose of updating simulation models. Emphasis is placed on the identified damping, which remains one of the largest challenges in OMA and is critical in flutter calculation. The effect of the measurement duration on the uncertainty in the modal parameters is also quantified using statistical distributions. The influence of different aircraft towing speeds on the force amplitude and the resulting relationship to the modal parameters is investigated as a key insight into making meaningful comparisons between GVT and TVT. Finally a comparison between the time-domain direct parameter estimator SSI, frequency-domain modal parameter estimator LSCF and a detailed GVT analysis of the aircraft is presented and discussed.

2 RESEARCH TEST CAMPAIGN

In 2011 a joint research test campaign was conducted between Airbus, DLR, and the French Aerospace Lab ONERA. The tests were performed on an A340-600 of the Airbus research aircraft fleet, at the Airbus facility in Toulouse. The objectives of the test campaign were to evaluate different research topics with focus on their ability to significantly reduce test time. The research topics, among others included sensor optimization, the potential of new excitation signals, non-linear identification, applicability of new optical measurement techniques, and TVT comparisons to GVT.

2.1 Description of the Aircraft

The Airbus A340-600, Figure 3, is a long haul passenger aircraft with a range of over 14 000 Km. It is powered by four Rolls-Royce Trent 500 engines with 250 kN of thrust each. The aircraft is 75 m long, 18 m high and has a wing span of 63 m. It can carry around 350 passengers with a max take-off weight of 280 tons. The A340-600 also includes state-of-the-art technologies such as the fly-by-wire system and composite structures to reduce weight.

Figure 3: Airbus A340-600.

2.2 Measurement Setup and Equipment

The aircraft was instrumented with 594 sensors including accelerometers, strain gages and linear displacement sensors to measure dynamic landing gear deflection. The data acquisition system consisting of multiple mainframes connected in a master-slave configuration was installed inside the cabin as seen in Figure 4. Both Piezo-resistive and ICP accelerometers were installed with a high spatial resolution on all the main components of the aircraft as shown in Figure 5.

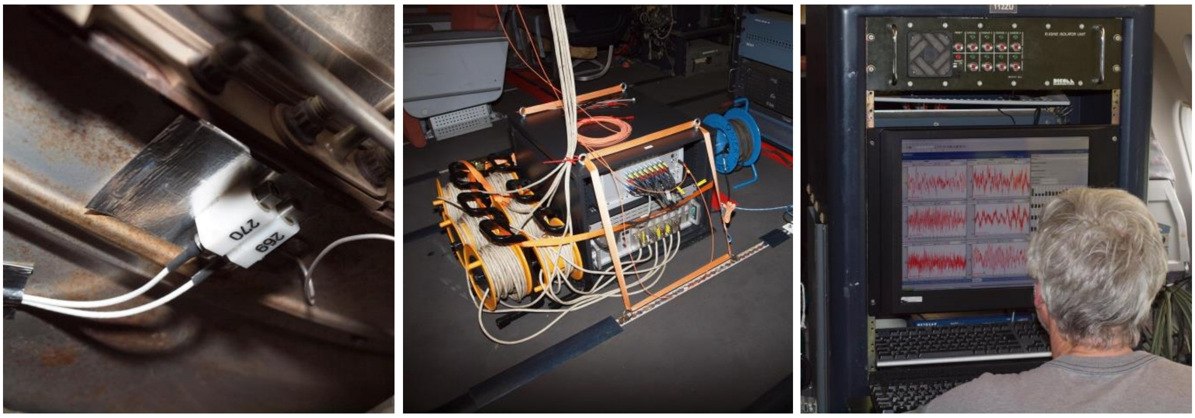

Figure 4: Piezo-resistive accelerometers (left). Measurement hardware (center). Data acquisition (right).

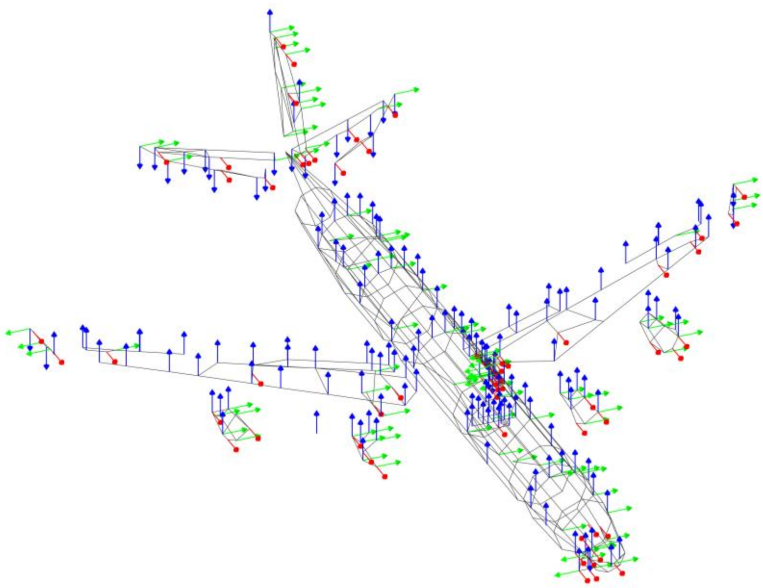

Figure 5: A340-600 geometry with measurement locations and directions.

2.3 Taxi Vibration Test (TVT) Procedure

The A340-600 was towed by a tractor as shown in Figure 6. Three TVT tests were performed at 5 km/h, 15 km/h and 27 km/h on the same day. Each run had a duration of 60 minutes with continuous recording of the operational responses. In between runs refueling of the center wing tank was performed to compensate for the fuel burn of the APU which provided the electrical power for aircraft operation and for the measurement system.

Figure 6: Taxi Vibration Test on the A340-600 long range aircraft at Airbus in Toulouse.

A satellite image of the GPS routes is shown in Figure 7. The 5 km/h and 15 km/h runs were performed around the Airbus A380 hall as seen on the left. The towing speed was kept as constant as possible also around the corners. The 27 km/h run required longer distances to maintain the required speed, making use of the extended taxi way as seen on the right. Based on insights from the ATRA A320-200 TVT it was not necessary to make special preparations of the track to reach the required levels of excitation. The actual operational boundary conditions including the stiffness of the tires, the shock absorbers driven out of their sticking-friction state and the gyroscopic effects of the rotating wheels provide both useful information for nose landing gear stability analysis (shimmy analysis) as well as a challenge to understand their effect on the elastic modes of the aircraft.

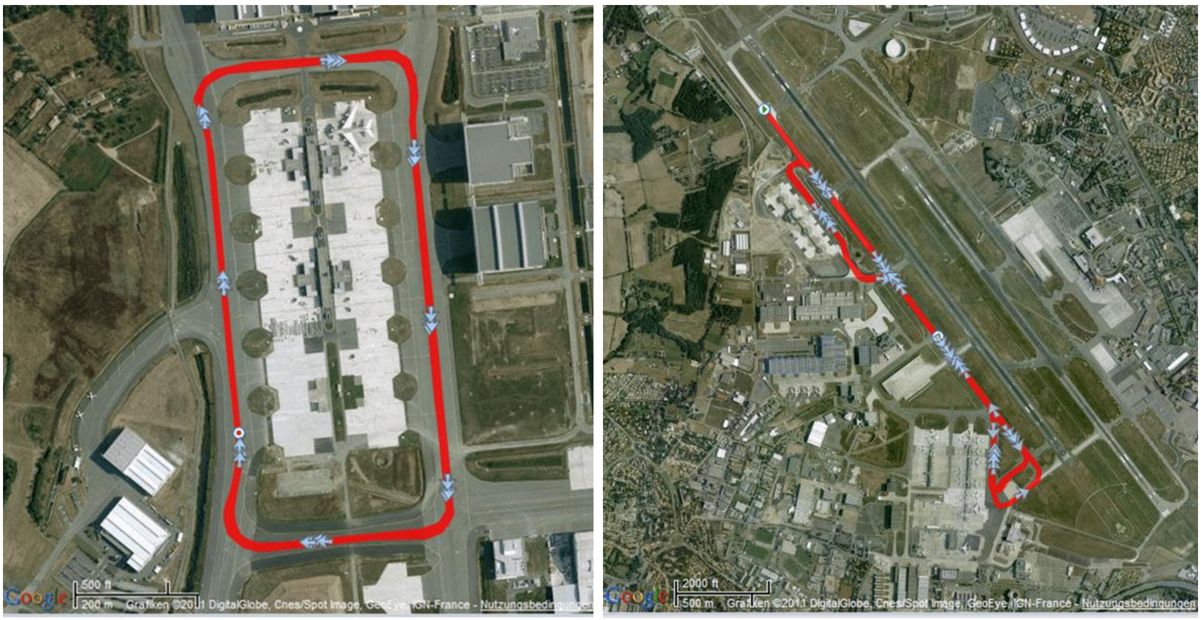

Figure 7: Satellite Route of Taxi Vibration Test (TVT).

2.4 Ground Vibration Test (GVT) Procedure

An extensive GVT [12, 13] was performed on the A340-600 with the measurement equipment and setup presented above in the test hanger as shown in Figure 8. The aircraft was tested in several configurations including on pneumatic suspension seen on the left, and on landing gear seen on the right. A comprehensive set of excitation signals were used to excite the aircraft in a range of different exciter configurations. The data acquisition, signal processing, modal analysis and modal correlation were performed by a multidisciplinary team of experts.

Figure 8: A340-600 during Ground Vibration Test (GVT).

3 RESULTS

The TVT data was analyzed using the in house tool box of the Department of Structural Dynamics and System Identification at DLR Göttingen. The toolbox uses Object-Oriented Programming (OOP) with optimized methods for processing and visualizing big data sets.

3.1 Modal Analysis

The acceleration signals were measured with a sample frequency of 256 Hz for 60 minutes. For modal analysis the data was first interrogated using a class to check for errors such as spikes, dropout, loose connections, faulty or detached sensors.

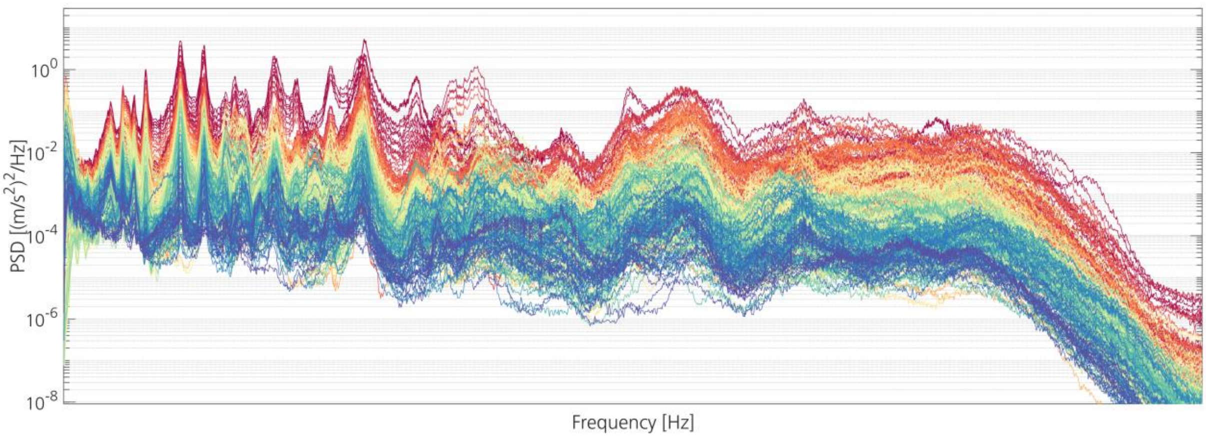

Figure 9: Auto Power Spectral Densities (APSDs).

The data was then decimated using a Chebyshev Type I lowpass filter to a lower frequency band which is of interest for FE model updating. The Auto Power Spectral Densities (APSDs) computed using a Hanning window with 66 % overlap is shown in Figure 9. The frequency limits cannot be shown for confidentially reasons. It can however be seen that the data contains a high modal density, that the structure is well excited in the band of interest and that a range of damping values can be expected based on the varying steepness of the peaks.

System identification was performed on the time data using data driven SSI with a range of Hankel block sizes from 8 to 20 and model orders 100 to 460. In order to perform the necessary mathematics such as QR factorization and Singular Value Decompositions on such a large channel count and long measurement duration an Intel Xeon E5 CPU with 196 GB or RAM was used.

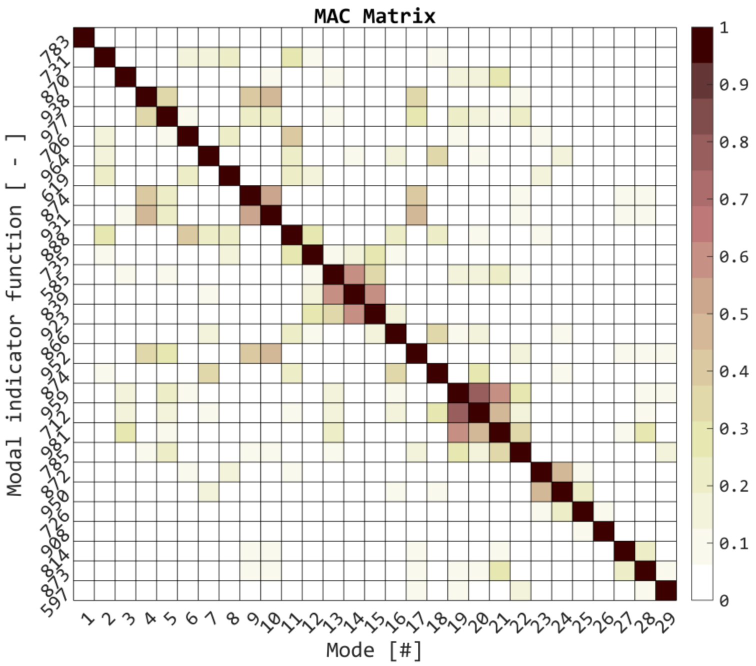

Figure 10: Auto correlation of TVT modes identified from 15 km/h.

The extended Modal Assurance Criterion (MACXP) matrix resulting from 60 minutes of data at 15 km/h is shown in Figure 10. In total 29 modes were identified in a sub-band from 0 Hz to 8 Hz. The diagonal matrix structure indicates a unique mode set. The Mode Indicator Function (MIF) according to Breitbach [14] provides a normalized indicator of the mode quality regarding the complexity of the mode shape, with 1000 indicating a real normal mode. While the structure is expected to have a certain degree of mode complexity due to different damping effects, the MIF values are seen to be in a good range. The mode shapes of two rigid body and 4 elastic modes are shown in Figure 11. The modes can be clearly identified as physical with high phase purity. From the 5 km/h and 27 km/h runs 20 modes and 32 modes could be identified respectively with the same identification parameter settings. This is due to higher excitation amplitudes during increased taxi speed.

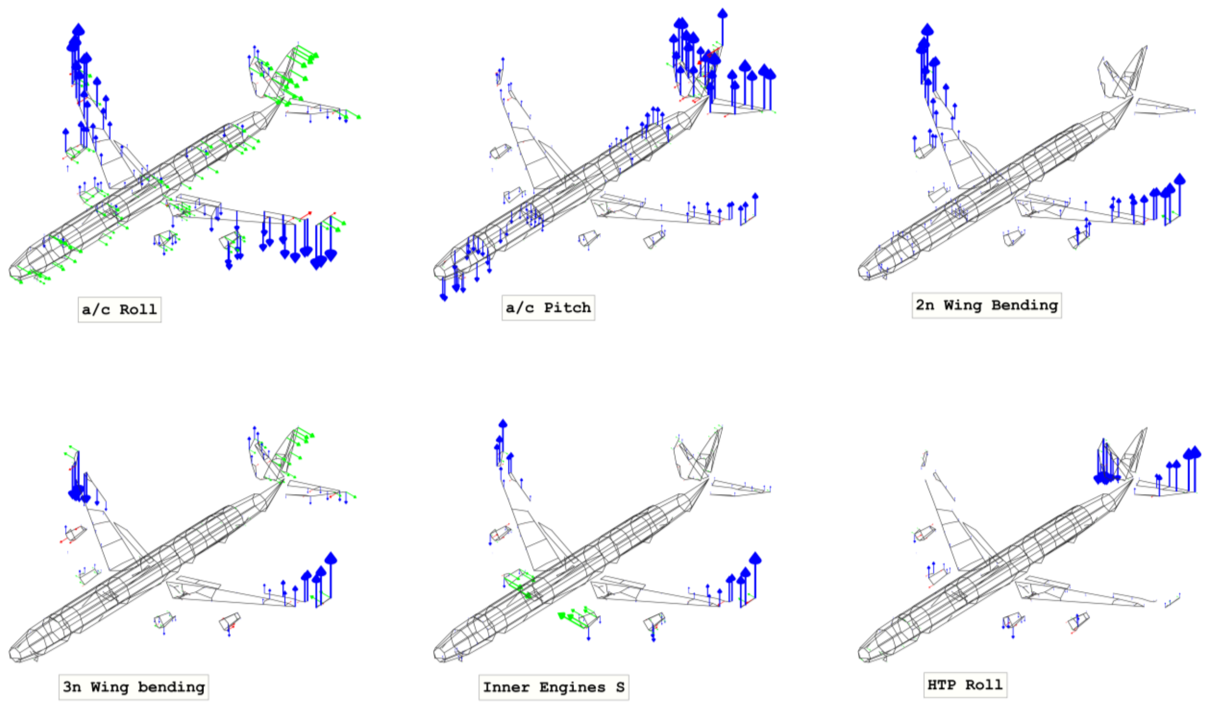

Figure 11: Six mode shapes of the A340-600.

3.2 Measurement Duration Confidence Intervals

An important question which has remained open is the effect of the measurement duration on the identified modal parameters. It is expected that a certain number of observations of a given signal will be necessary to obtain a desired confidence. Furthermore this will also depend on the level of the excitation force and will vary from mode to mode depending on which part of the structure participates most. The measured time data over 60 minutes during 15 km/h TVT is shown in Figure 12. The filtered data has an average RMS value of 0.08 m/s^2 during 5 km/h, 0.25 m/s^2 during 15 km/h, and 0.40 m/s^2 during 27 km/h. The effects of four measurement durations namely the full 60 minutes, 20 minutes (blue window), 15 minutes (green window) and 5 minutes (red window) were investigated.

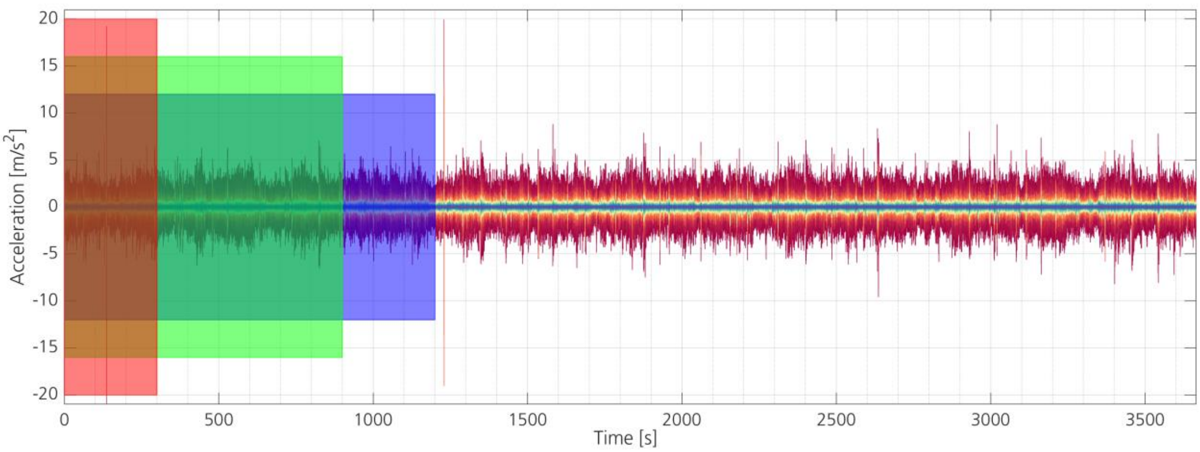

Figure 12: Measured time data during 15 km/h TVT with 20, 15 and 5 minute measurement duration windows.

The statistical distributions of the modal damping identified by SSI using the same algorithm parameters for the four measurement durations are shown in Figure 13. The six modes correspond to those displayed in Figure 11. The plot shows the mean damping of each mode family as a function of model order by the solid red line, the Standard Error of the Mean (SEM) by the opaque red box and the Standard Deviation (SD) by the opaque blue box. The jittered dots are the damping values which provide the careful observer valuable information about the distribution of the data, which are sometimes hidden by summary statistics.

Firstly one immediately notices that there is no trend of increasing scatter in the data as the measurement duration is reduced. While the mean is slightly reduced for mode 1 the other modes remain stable with high SEM. The small SD of the damping ratio for modes 2, 3, 5 and 6 indicates little scatter and therefore high certainty in the identified damping. The jittered data shows high density around the mean for most modes, indicating that the result converges at increasing model order. It is also possible to identify outliers most notably for mode 4 in the 60 minute data window. Another observation was that the total number of modes identified varied with measurement duration from 29, 32 and 30 modes from 60, 20 and 15 minutes of data and was reduced to 19 modes from 5 minutes. Below 5 minutes no physically meaningful modes could be identified for the 15 km/h run. This equates to approximately 480 observations of the first elastic mode with a Hankel matrix size 10024 x 9573.

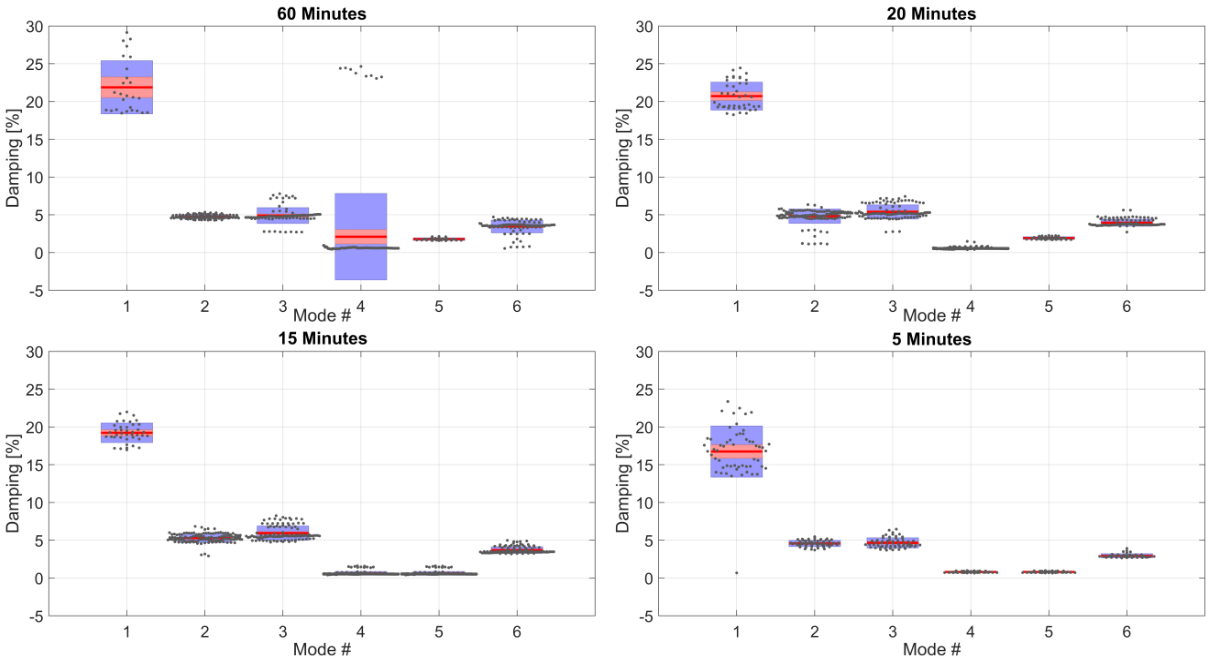

Figure 13: Statistical distributions of modal damping identified from four different measurement durations.

3.3 Modal Acceleration Spectra

A critically important observation from modal testing conducted on aircraft by DLR is the dependence and subsequent relationship between the excitation force level and the modal parameters. This nonlinearity is inherent in aircraft structures which are made from many different materials and assembled with various types of joints. The amount of variation of the modal parameters depends on the associated mode and the range of the force amplitude. This is absolutely fundamental in order to compare and validate the TVT and GVT results. It is also important in order to quantify what a ‘good’ or logical frequency and damping value for a particular mode should be.

During TVT it is however not possible to accurately measure the input forces, this is also the case for flight testing for example. A metric was therefore required which could provide insight into the unknown excitation force amplitudes. Since the structural response is dependent on the excitation force, the structure acts as a filter on the input forces. It was therefore decided to use the amplitude of the modal acceleration spectra as an indicator of the input forces subject to an unknown scaling. The method was performed as follows: the modal parameters from SSI were first rotated to maximum real part as shown in Figure 14 for a/c Pitch and 3n Wing Bending.

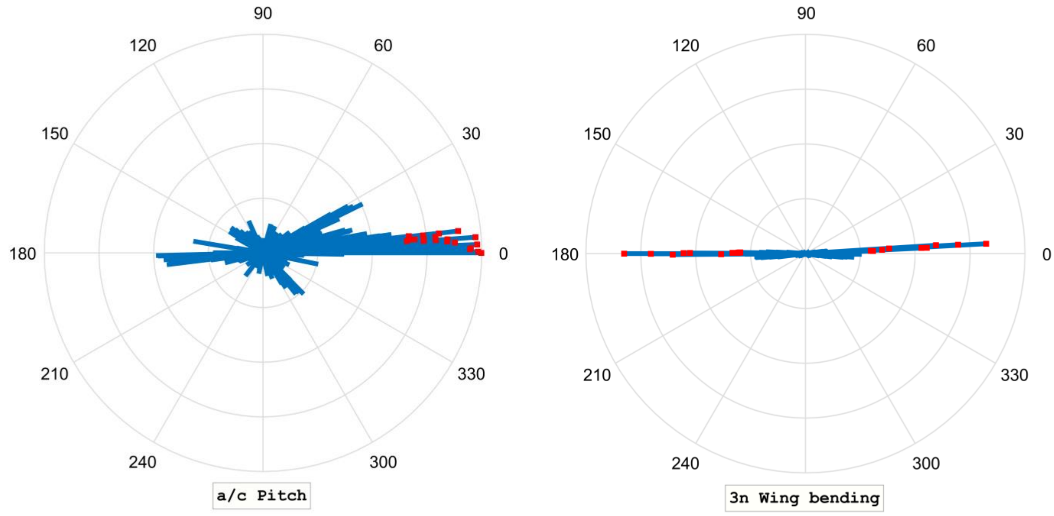

Figure 14: Complexity plots for a/c Pitch and 3n Wing Bending.

The 20 largest eigenvector amplitudes of each mode were then selected as indicated by the red squares. The time data of the corresponding sensors was then automatically selected and used to calculate the APSDs, with the same signal processing parameters for all data sets. The modes are then tracked and clustered using the MACXP. The GVT data is then imported, tracked in accordance to the TVT results, and the corresponding APSDs are calculated. The modal acceleration spectra in the surrounding band of each corresponding mode from GVT, TVT 5 km/h, TVT 15 km/h and TVT 27 km/h are then plotted on a log scale as shown in Figure 15 for a/c Pitch and 3n Wing Bending. Here it can be seen that response amplitudes from TVT 15 km/h and 27 km/h are significantly larger than the GVT response amplitudes. The 5 km/h response amplitudes are slightly lower for a/c Pitch and higher for 3n Wing Bending. When taking into account the friction type nonlinearity introduced by the landing gears, it can therefore be expected that the TVT results should have lower frequencies and higher damping than the GVT results. Similarly, the TVT results from the 27km/h should have lower frequencies and higher damping than the modes from the 5km/h.

3.4 Non-Linearity

In order to investigate the relationship between the force level and the modal parameters, the non-linearity plots for a/c Pitch and 3n Wing Bending modes are presented in Figure 16 and Figure 17. The normalized frequencies are shown by the red curve and the normalized damping by the blue curve. Both parameters are normalized by the GVT result. The MAC matrix shows the correlation of the mode shape across the 4 cases. The orthographic view illustrates the associated mode shape from the 15 km/h TVT identification.

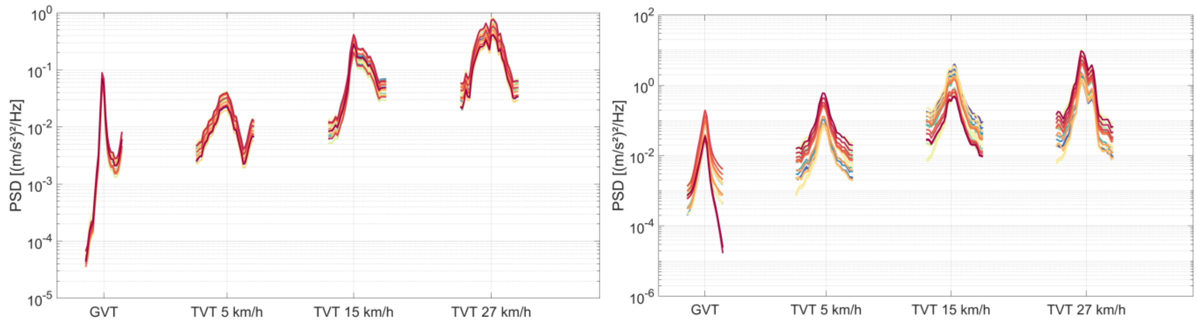

Figure 15: Auto Power Spectral Amplitudes. a/c Pitch (left) and 3n Wing Bending (right).

It can be see that identified damping of the a/c Pitch mode increases from GVT to TVT and then further increases with higher TVT taxi speeds. From the mode plot in Figure 16 it can be seen that the Nose Landing Gear (NLG) is activated during TVT. From the mode shape comparison in Figure 21 in the Appendix it can be seen that the NLG is not active during GVT. When the NLG is active the hydraulic damping mechanism is in sliding friction which has the effect of increasing the damping. The increase in damping with higher taxi speeds was as expected from the increasing modal acceleration spectra in Figure 15. The physical mechanisms responsible for force dependent damping have been investigated in literature by [15]. The natural frequency of the a/c Pitch mode decreases from GVT to TVT as a result of reduced stiffness when the landing gear is in the active or sliding friction state as one could imagine. The frequency decreases further during 15 km/h TVT as expected however slightly increases during 27 km/h breaking the trend. The reason for the final increase requires further investigation. From the MAC matrix it can be seen that the mode shape changes slightly from GVT to TVT, mostly due to the participation of the NLG, and again from 5 km/h to 15 km/h but then remains very similar at 27 km/h.

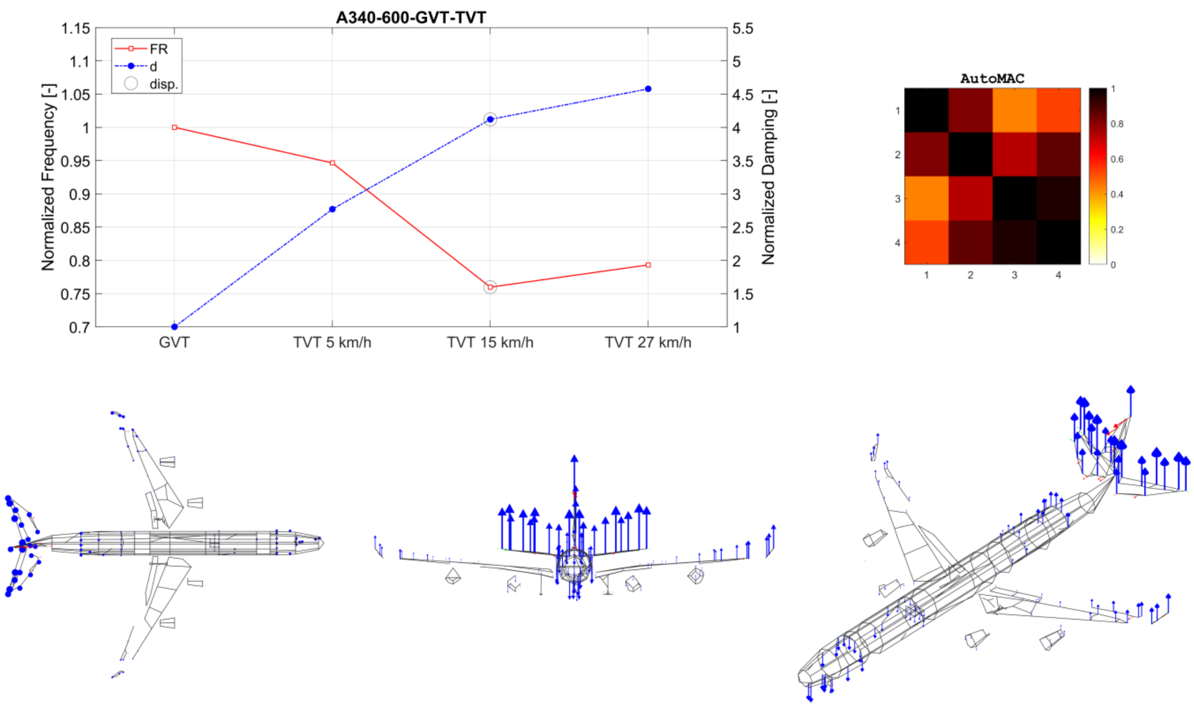

Figure 16: Non-Linearity A340-600 a/c Pitch.

The 3n Wing Bending mode in Figure 17 shows a decrease in natural frequency from GVT to TVT as well as during increasing taxi speeds. The maximum normalized frequency variation of 0.97 might seem extremely small, however considering the high modal density and high certainty on the frequency estimates translates into a Δf which could change the mode order and therefore play an important part in the updating of the FE model. The damping of the 3n Wing Bending does not show an increasing trend. The landing gear is observed to be inactive in the mode plots in Figure 17 and Figure 22 which is one factor. The increase in damping from 5 km/h to 15 km/h followed by decrease to 27 km/h is not necessarily incorrect, but requires further identifications to increase the confidence. Finally the MAC matrix shows that the mode shape is highly correlated between GVT and TVT and is not highly influenced by the changing boundary conditions of the landing gear activation or increased force amplitudes at higher taxi speeds.

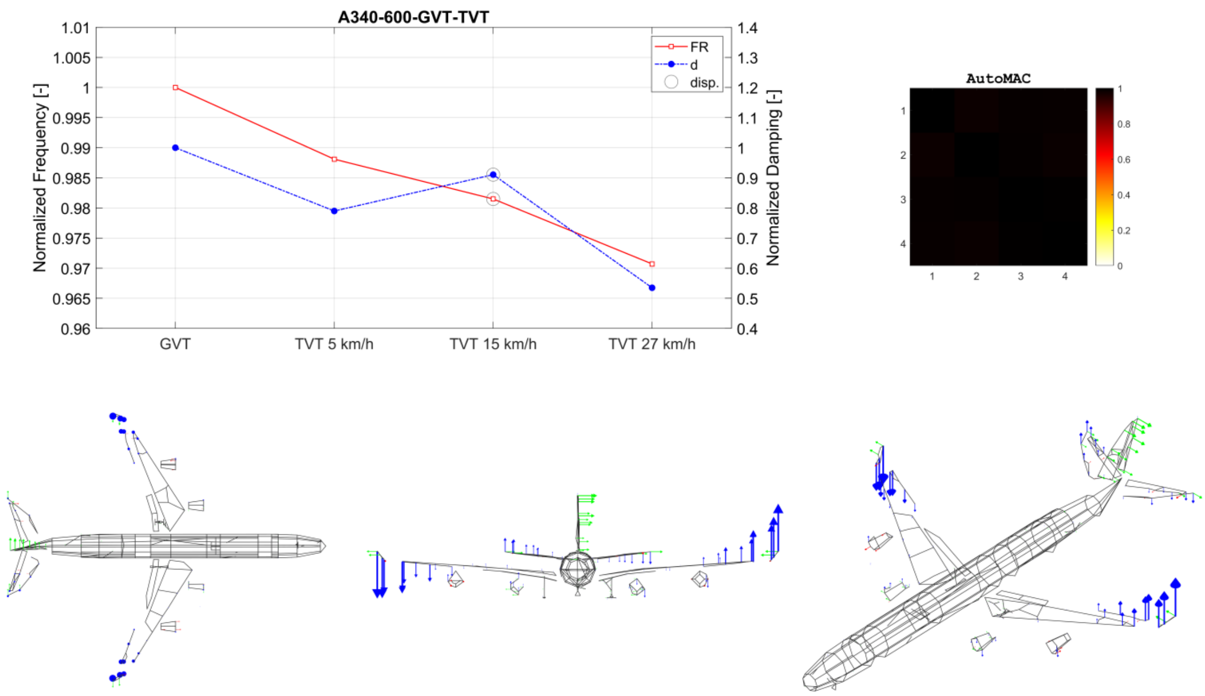

Figure 17: Non-Linearity A340-600 3n Wing Bending.

3.5 TVT vs GVT Comparison

A main objective of this work is to establish the TVT as an efficient means for aircraft certification. In order to achieve this, the TVT must be validated by comparison to the current certification standard which is the GVT. The final modal model resulting from the GVT was assembled from best quality modes selected from a huge amount of modal data sets obtained from modal analysis of data from many excitation configurations. The DLR Correlation Tool is a dedicated tool streamlined for this task and has matured over more than 15 years of application in large GVT campaigns. The main mode from each of the first 25 GVT mode families is selected as the reference. The normalized eigenfrequencies resulting from SSI 15 km/h TVT, LSCF 15 km/h TVT and GVT Configuration 1 (SC1P) are shown in Figure 18. Upon first inspection it may not seem that TVT compares very well to GVT. However it is critical to remember the influence of the excitation amplitude on the modal parameters. Since the response spectra were lower for GVT than for TVT 15 km/h for a/c Pitch and 3n Wing Bending (Figure 9) it is expected that TVT frequencies should be lower than the GVT frequencies for these modes, as seen in the figure below. Furthermore the response spectra are in general lower during GVT as compared to TVT which explains the trend of both TVT estimates (red dots SSI, black cross LSCF) lying under the black line of normalized GVT frequencies.

Since most of the main modes from GVT were chosen from engine excitation it is not surprising that the engine modes show a smaller TVT-GVT deviation due to more similar response amplitudes, as well as for 3 engine modes which have higher TVT frequency estimates. SSI and LSCF show a high level of similarity regarding identified eigenfrequencies, which increase the confidence of the TVT results. The two Rigid Body Modes (RBM) show the largest deviation between GVT and TVT caused by the activation of the landing gear during TVT which reduces the stiffness of the system. Careful observation further reveals certain bands or modes which are lower during TVT than GVT (A/C Roll - OutEngLatSym), a second band (InEngLatAnti - HTPForeAftAnti) with more variablitly but several higher TVT estimates and the final band (InEngVertSym – 6nWingBending) with slightly lower TVT estimates as well as smallest deviation. This is due to the varying response amplitudes, which can be seen in the spectra in Figure 9, which is as a result of the excitation frequency which is not constant amplitude and white, as well as the spatial distribution of the input forces which comes mainly through the landing gear during TVT. It is also expected that a crossover frequency exists where predominantly lower frequency TVT energy content drops below that of GVT. This is however expected to be above the critical range for the purpose of model updating for aeroelasticity calculations. Trend of SC1P

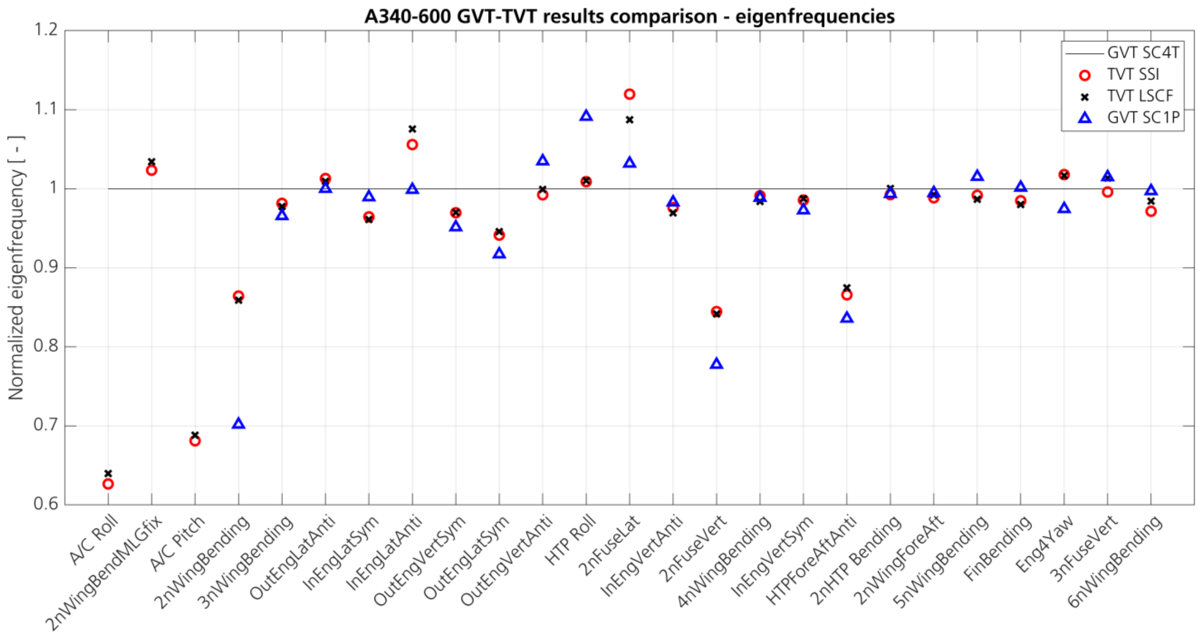

Figure 18: Normalized frequency deviation of correlated modes from GVT and TVT.

The normalized damping coefficients of the modes are shown in Figure 19. Even though flutter analysis is performed in the beginning for the undamped structure, accurate identification of structural damping is nonetheless important, because any additional structural damping can shift flutter critical speeds upwards. However it remains the most challenging task to estimate damping accurately from measured data. The damping has also been observed to vary far more as a result of the force amplitude than the frequency. For a/c Pitch in Figure 16 the damping shows a max variation of 4,5 times compared to the max frequency variation of 0,75.

Firstly it is seen that the SSI TVT damping estimates are in general two or more times larger than the GVT. This is in perfect agreement with the larger response amplitudes during TVT. The influence of the landing can also be seen on modes where the landing gear shows high participation, for example A/C Roll. Since LSCF has been shown to be biased towards underestimating damping [16], the similarity between LSCF 15 km/h TVT and GVT is coincidental due to bias. The effect of different amplitudes in the spectral bands, Figure 9, can also be observed for the damping estimates. The similarity between GVT SC1P and SC4T indicate that the air suspension in SC1P has a smaller effect on the damping than the force amplitude with higher TVT taxi speeds. Further investigations to compare the force levels of the main modes from SC1P and SC4T are however also required.

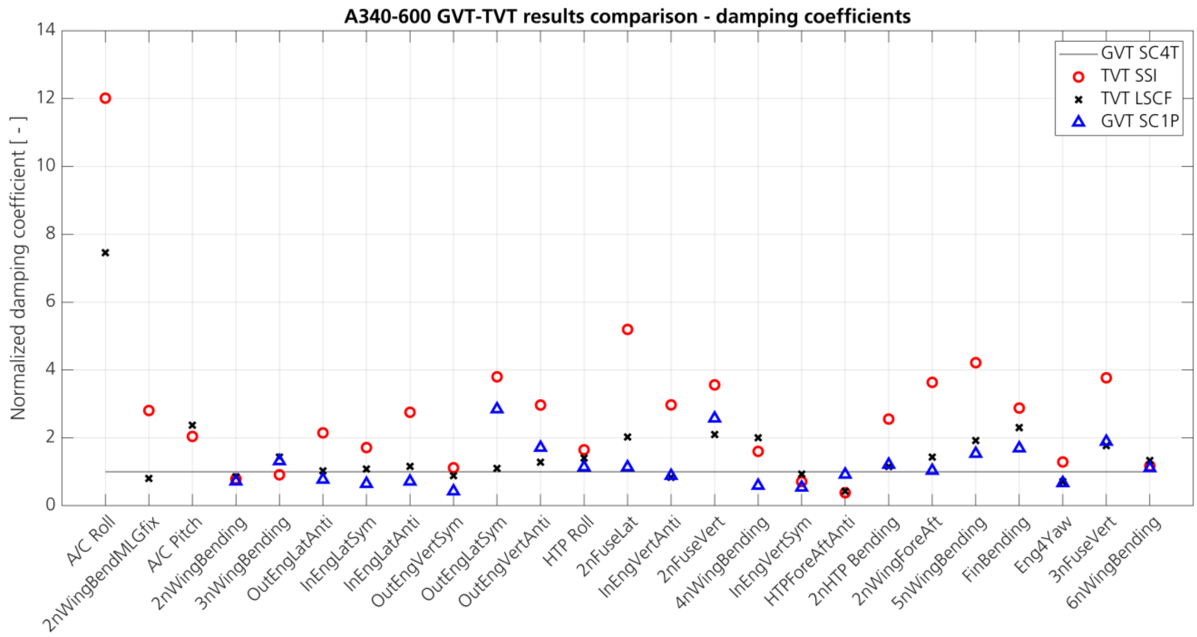

Figure 19: Normalized damping deviation of correlated modes from GVT and TVT.

The comparison of MAC matrices from different towing speeds in Figure 20 underlines that higher speeds (15 and 27 km/h) yield more identified modes.

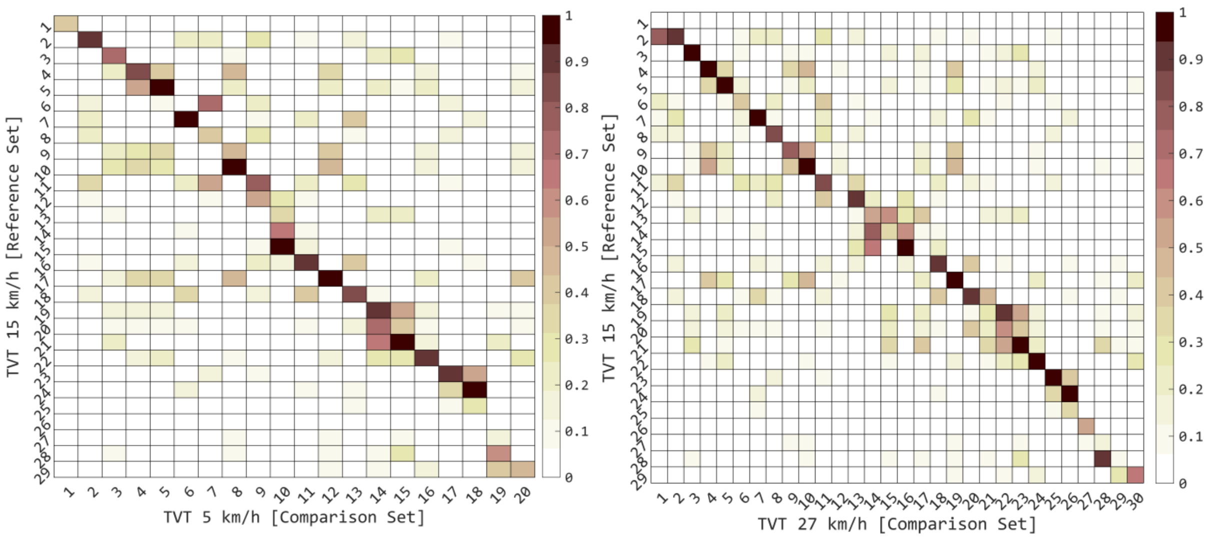

Figure 20: Comparison of MAC matrices between different towing speeds 5, 15 and 27 km/h.

4 CONCLUSIONS

In this work the potential of the Taxi Vibration Test (TVT) method was both demonstrated and extended as a time efficient alternative to the classical Ground Vibration Test (GVT) for aircraft certification. The optimal use of advanced signal processing and system identification techniques together with highly capable computing hardware allowed the accurate identification and post processing of modal parameters from big data sets. A comprehensive set of modal parameters were identified using the Stochastic Subspace Identification (SSI) method. The influence of the measurement duration on the modal parameters was investigated. It was found that shorter measurement durations did not show trends of increasing uncertainties, and that 5 minutes of data at 15 km/h resulted in low Standard Error of the Means (SEM) and Standard Deviations (SD). Shorter measurement durations, as well as lower taxi speeds did however result in fewer modes identified. The measurement duration should therefore be chosen in accordance with the taxi speed and objectives of the test campaign (i.e. model updating in a specified frequency band). The modal acceleration spectra were proposed as a metric which could provide insight into the unknown excitation forces. This is due to the strong relationship between the excitation force amplitude and the modal parameters. This non-linear phenomenon is therefore crucial for meaningful comparisons between GVT and TVT. Here it was found that the 15 km/h and 27 km/h TVT had significantly larger response amplitudes than during GVT, from which it is inferred that the energy of the excitation force is higher in this band during TVT than GVT. As a result it was expected that the frequencies from these TVT runs should be lower than GVT and that the damping should be higher. The effect of the landing gear to increase damping and reduce stiffness was also observed for modes were the landing gear was seen to be active in the mode shape plot. Non-linearity plots provided further insight into the difference between GVT and TVT as well as the relationship between taxi speed and frequency, damping and mode shape. In general the observations made from these plots could be substantiated by known physical phenomena. A comparison of 25 modes from two GVT configurations and three TVT configurations confirmed the hypothesis of the force dependency of the modal parameters. It was found that the natural frequencies were in general lower during 15 km/h TVT than during GVT and that the damping ratios were higher during TVT than GVT. The amplitude of the damping ratios identified using SSI as well as the resulting damping trends are a significant improvement over LSCF and will be very important for accurate flutter calculation. The re-analysis of the A340-600 TVT data showed that the new tools developed at the German Aerospace Center in Göttingen are now capable of the final maturation of the TVT method for aircraft certification.

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APPENDIX

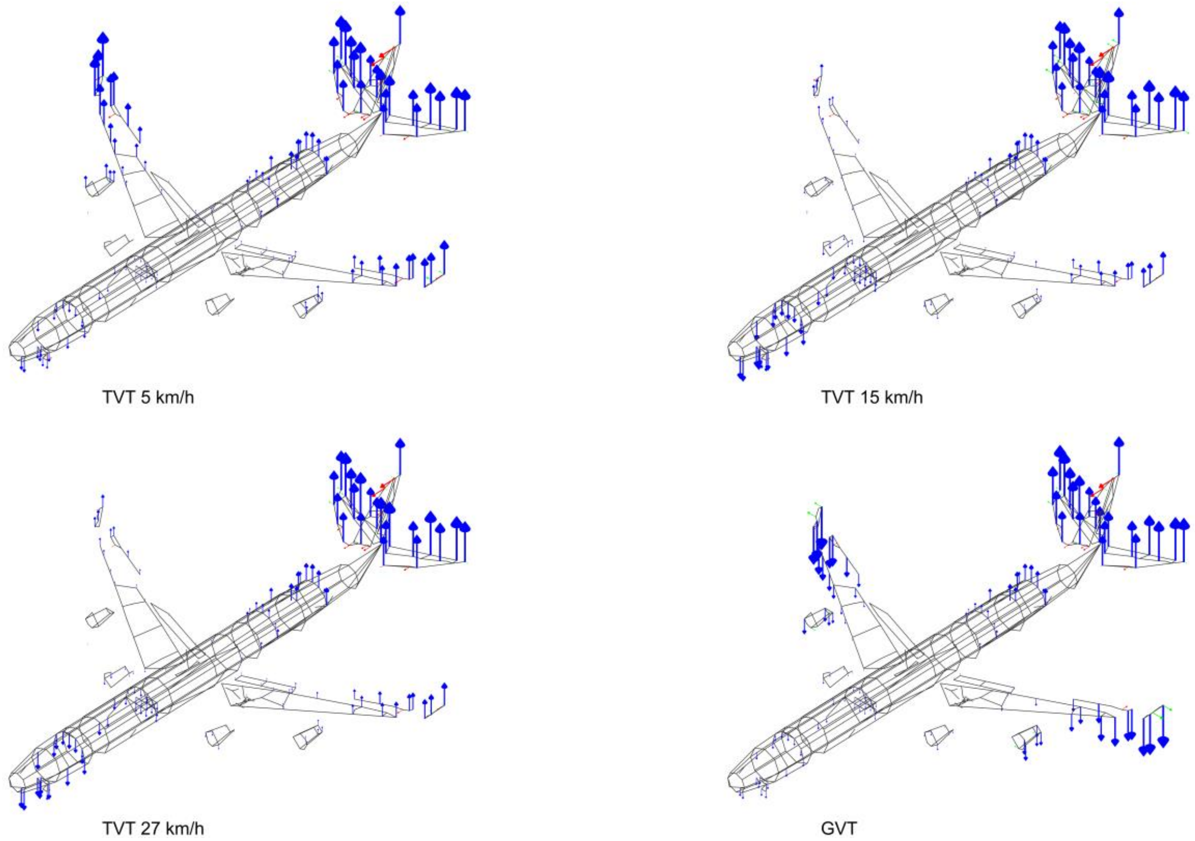

Figure 21: Mode Shape Comparison a/c Pitch.

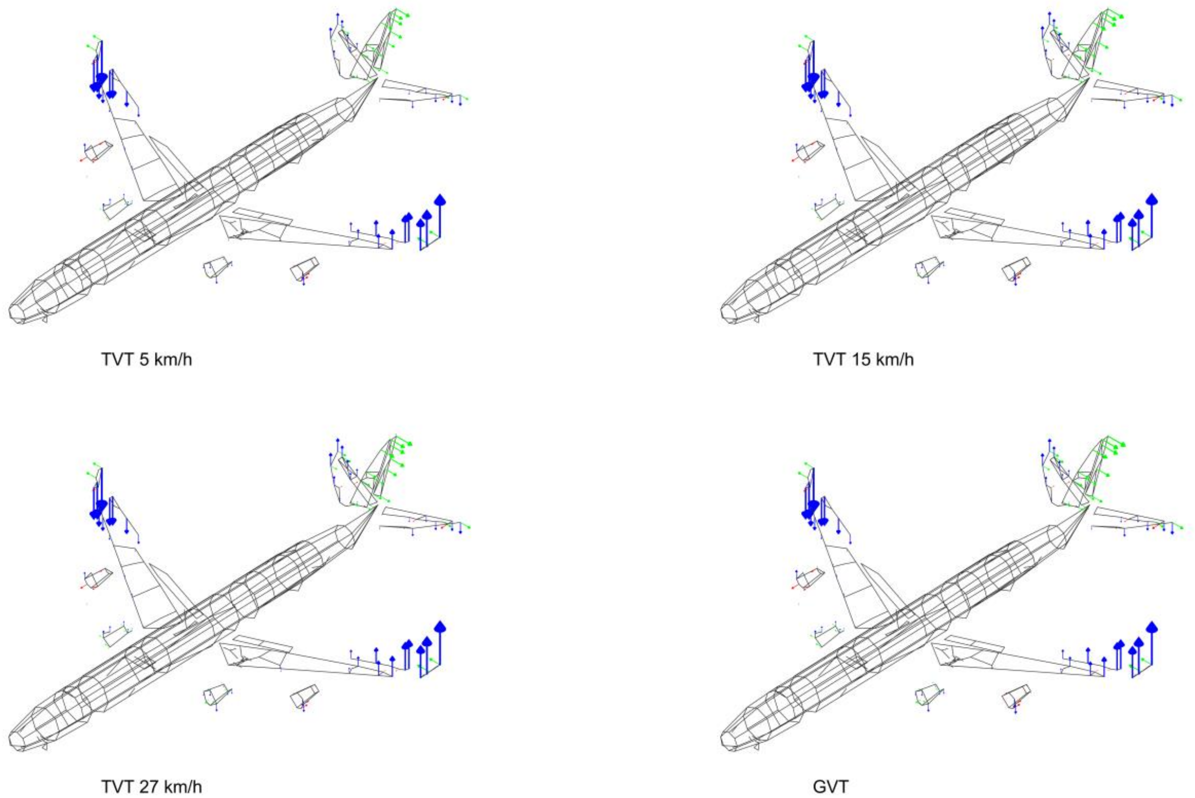

Figure 22: Mode Shape Comparison 3n Wing Bending.