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Validation of an Acoustic Travelling Wave System Through Forced Response Analysis of a Research Blisk

Mitchell R. Cosmo, Jianfu Hou, Marco S. Attia

Aerospace Division, Defence Science and Technology Group, 506 Lorimer Street, Fishermans Bend, Victoria, 3207, Australia

Abstract

The validation process of an acoustic travelling wave system (TWS) is presented. This system is intended to be used for the characterisation of blisks and their associated mistuning for in-service blisks. The system developed by the Defence Science and Technology Group was validated through comparing differences between numerical (finite element method) and experimental modal frequencies of a 12-bladed research blisk. Two cases were considered; an undamaged case and one with simulated foreign object damage (FOD) – a common source of mistuning in blisks. The two sets of results showed a difference of less than 2% between modal frequencies, and this can be considered reasonable for a completely non-contact system. The TWS was sufficiently sensitive to detect differences between blisks with simulated FOD and an undamaged blisk. Sources of errors which may be present in the system are discussed and final outcomes are disclosed.

Keywords: Blisk, travelling wave, rotor dynamics, forced response, modal analysis

Background

High Cycle Fatigue (HCF) related failures are a serious concern for the modern gas turbine engine. These types of failures can occur rapidly without any indication, causing catastrophic damage to an engine; therefore there is a significant push to investigate the causes of HCF within gas turbine engines that utilise blisks (bladed disks) or integrally bladed rotors (IBRs) within the compressor stage. The requirement to examine these blisks for mistuning – small variations between blades caused by manufacturing tolerances, material differences or damage – is therefore essential. To enable experimental analysis of the effects of mistuning on blisks, an acoustic Travelling Wave Excitation System (TWS) has been developed by Aerospace Division of the Defence Science and Technology Group (DST) in Fishermans Bend [1].

Whereas traditional rotors are made up of a blade and disk subassembly, blisks are by design, a single piece of material made up of blades and disk. The lack of any major joins also reduces the probability of crack initiation and/or propagation at the blade root. Although there are many advantages to using blisks in aircraft engines, they are highly susceptible to HCF due to their lack of any additional damping from traditional blade attachments, resulting in high vibration response throughout the component; which can be significantly worse for a mistuned blisk. Mistuning affects the original design specifications of the blisk and even small differences between blades can cause unintended higher vibration amplitudes and stresses in the blades which can concentrate in only one or few blades (termed mode localisation [2]). The high stresses in these localised regions contributing to the onset of HCF.

In order to detect the extent of mistuning for a particular blisk, it is necessary to excite a blisk and analyse the vibration modes (or resonant frequencies). Travelling wave excitation is one method which has been used [3-9] to analyse mistuning. In comparison to oil jet excitation within a spin-test setup, travelling wave excitation is inexpensive. These types of systems can utilise either magnetic or acoustic excitation to excite a blisk. Such non-contact excitation methods are commonly used in conjunction with a scanning laser vibrometer for data acquisition and visualisation of the vibration modes and mode shapes. A laser vibrometer is preferred to strain gauges as they can change a blisk's dynamic response.

Since HCF is one of the critical issues being faced by today's gas turbine engines, DST are developing their expertise in HCF measurement, analysis and mitigation, in order to provide independent airworthiness and sustainment advice to the Australian Defence Force (ADF). A major driver for DST's HCF capability is Australia's acquisition of the F-35 Joint Strike Fighter (JSF). The TWS has the capacity to support this venture through verification of blisks following Foreign Object Damage (FOD), Domestic Object Damage (DOD) or following repair of such damage.

Numerical Methods

The Finite Element Method (FEM) was applied to CAD models representing the research blisk for both cases described; an image of which can be found in Figure 1. The blisk was meshed using 3D shell elements and a force boundary condition was applied at the central hub of the blisk. At the opposite side of the blisk, a compression-only support, the same size as the force boundary condition, was placed. The inner hub of the blisk also allowed for scoping of a compression-only support to simulate the bolt used on the TWS rig. A modal analysis was performed to determine the natural frequencies and modal shapes of the tuned and mistuned research blisk models. Average material properties for the grade of stainless steel were used in the analysis with a Young's modulus of 193 GPa, a density of 8000 kg/m^3 and a Poisson's ratio of 0.31.

A total of 26 modes were extracted from the structure for both the tuned and mistuned case. The first and 14th modes were excluded due to a lack of fixation in the rotational-Z direction. The first family of modes (first 12 relevant natural frequencies) relate to the frequencies examined under experimental testing. Each of the first 12 natural frequencies were also arranged to display the mode shape solution under the equivalent (von-Mises) stress and total deformation conditions in order to examine locations of high stress on the blisks.

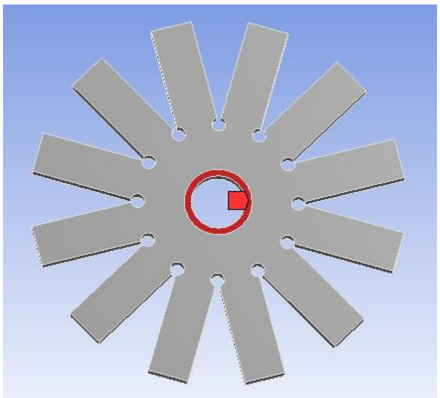


Figure 1. Research blisk geometry with TWS fixture boundary conditions shown.

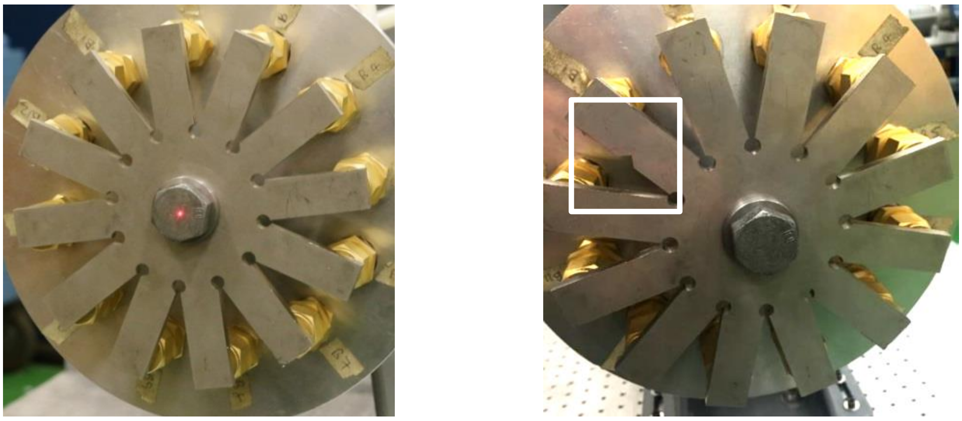
The Travelling Wave System and Testing

The two blisks were examined experimentally in order to extract the modes of baseline and mistuned models. The TWS is comprised of three main sub-systems, described in [1]; the excitation sub-system, blisk fixture sub-system and the data acquisition sub-system. The excitation sub-system consists of a function generator (with a touch screen Graphical User Interface (GUI)) to produce the requested amplitudes, frequencies and phase angles desired by the user (or values associated with a particular Engine Order (EO)). Through the GUI it is also possible to activate a sweep function; which permits selection of lower and upper frequency limits and time to generate one full sweep. Signals are sent from the function generator to the attached amplifiers and onto speakers, producing the acoustic output.

The blisk fixture was mounted on a vibration isolation table modified to house speakers and the blisk fixture unit. For the current experiment, a 12-nozzle fixture was mounted so acoustic excitation could be provided directly to each individual blade of the research blisk. It was possible to manually adjust these nozzles separately to adjust the gap size (distance between the blisk and nozzle opening). Speakers were wired directly to the amplifiers via 12 independent channels. The output from the speakers was then delivered to the blisk through PVC tubing. A scanning laser vibrometer was used as the measurement tool for vibrations of the blisk. The equipment included the scanning head, sensor head, junction box and vibrometer controller, and the data acquisition device (PC with PSV software installed). This method of data acquisition allows for measurement without any physical contact to the blisk.

The research blisk provides a baseline for testing the TWS. Its simple structure simplifies the analysis, which is important for these preliminary experiments. Future experiments will deal with more realistic and consequently more complex blisks. DST has designed the blisk to mimic the modes appearing within the 700-1200 Hz frequency range of an in-service blisk. These pieces were designed to be simple and thus easy to manufacture and mount. There were two cases considered within the experiment conducted in this report; an undamaged case which will be treated as tuned, and a mistuned case which had significant damage on one of the blades represented by a notch; these blisks are shown in Figure 2(a) and (b) respectively.

Each blisk was tested, including excitation of each EO to validate the performance of the system. The dataset for these tests were then averaged for individual points on the blisk. Data equated from this averaging showed similar frequency for each mode and general trends for amplitudes were also maintained. Therefore individual scans show a sense of repeatability for the 12-bladed research blisk described.



(a) *(b)*

Figure 2. Research blisks used in experimentation. (a) Undamaged, (b) Damaged

Result Comparison

Comparison of the numerical to experimental behaviour of the tuned (undamaged) research blisk involved overlaying the FEA (Finite Element Analysis) results onto the response spectrum plot obtained from experimental data, as shown in Figure 3. The black vertical bars represent the natural frequencies obtained from the FEA; as there is no magnitude associated with these frequencies, only a location is available. Results show good correlation between the numerical and experimental values; with a maximum difference of < 2%. As the TWS is a completely non-contact system, this error can be considered reasonable.

Figure 4 shows a similar plot for the damaged research blisk. Results for the mistuned case also show good correlation with numerical values; with a maximum error of < 2%, much like the tuned case. From Figure 4, it can be seen that the first and second modes have a lesser difference than the tuned case. Split repeated modes (725 Hz, 810 Hz, 972 Hz, 1085 Hz, 1141 Hz) were, in general, more accurate than their baseline counterpart. Figure 5 is a comparison of the experimental results between the damaged and undamaged research blisk. It gives an example of the split modes and differences in dynamic response.

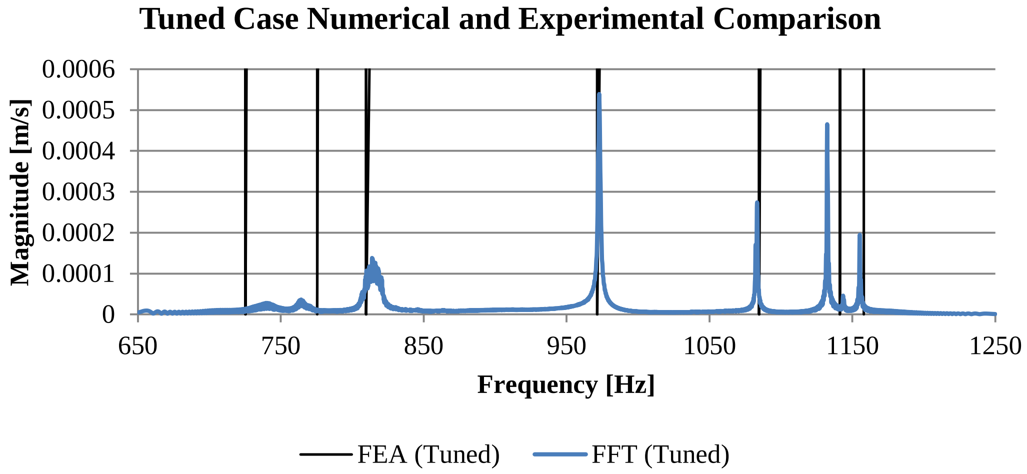


Figure 3. Response spectrum plot of experimental data overlayed with FEA modal frequencies for the undamaged research blisk

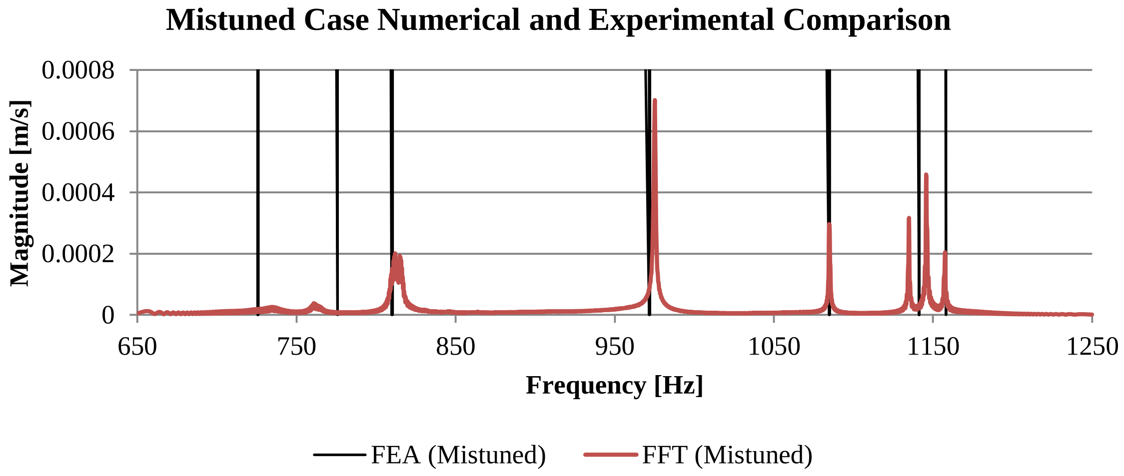


Figure 4. Response spectrum plot of experimental data overlayed with FEA modal frequencies for the damaged research blisk

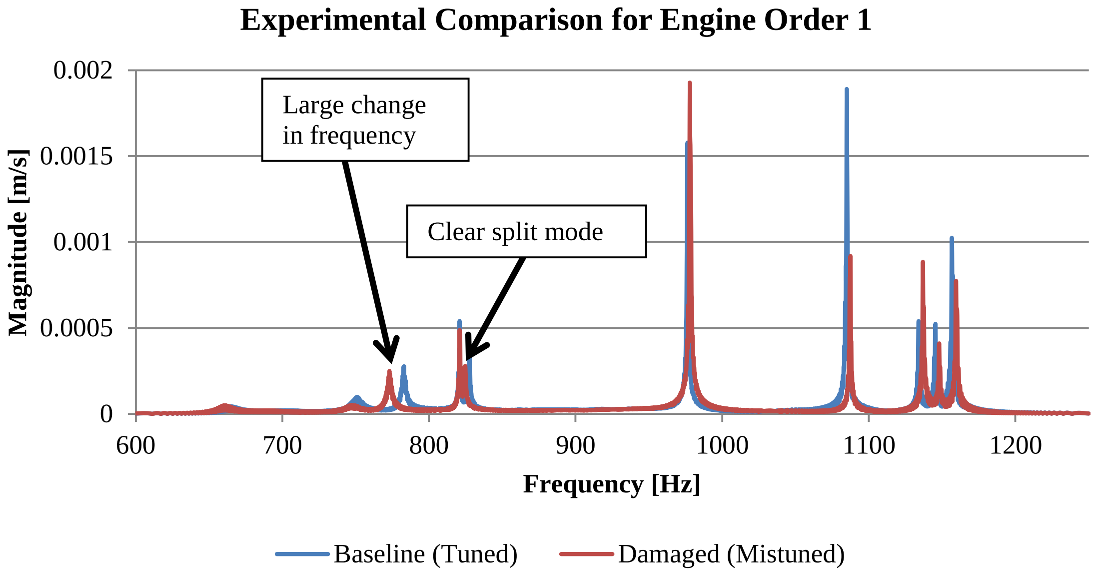


Figure 5. Comparison of experimental results for the damaged and undamaged research blisk

Discussion

The TWS was validated through the direct comparison of numerical and experimental results of a damaged and undamaged research blisk. The sensitivity of the TWS was sufficient to detect differences between the undamaged blisk and one with simulated FOD. This sensitivity was shown from the small differences detected (1-2 Hz) for the experimental case. However, the experimental frequency differences were large in comparison to the numerical results. This may be explained by the fact that the research blisk is represented as a tuned blisk for the numerical analysis, thus no external variations (such as manufacturing imperfections) were introduced in the FE model which may be present in the physical specimen. Nevertheless, the geometric differences between the FE models can be assessed through the increase in frequency of the secondary repeated mode.

Numerical predictions are shown to be accurate for both blisk cases, with a maximum difference of less than 2% between the experimental and numerical results. These results show that the introduction of a force boundary condition from the initial testing completed in [1] increases accuracy of the model. This force introduces a local stiffening effect; decreasing the lower-frequency modes in order to relate more closely with those observed experimentally. This produces a better match to the experimental frequency patterns across both blisk cases when compared to previous testing.

There are a number of factors that could account for remaining discrepancies between the results, such as:

1. The formation of a heat affected zone on the surface of the physical research blisks during their manufacture by laser cutting. Due to this process, stiffness and density of the stainless steel may be inconsistent throughout the thickness of the research blisk.
2. Anisotropy of the material properties due to the rolling of the stainless steel into sheet.
3. The non-contact method of experimental testing. As sound waves are projected onto the blisk, errors may be introduced in the form of external noise (internal or external from the test facility), sound-wave reflection, or large vibrations from other onsite sources. For the latter case, the vibration-isolation table aims to reduce these large

vibrations. However, the good repeatability of results throughout the experimental testing indicates that these factors are of lesser importance.

4. Low output power from the speakers; causing a less-than-optimal force application to the blade tips.

Such factors were not included in the FE models; therefore these small discrepancies were not unexpected.

Differences due to simulated FOD were observed as shown in Figure 5. The mechanisms are the subject of on-going work. As the mistuned case is unsymmetrical, the change in repeated modes is expected. It is assumed that the fractionally lower mass and reduced stiffness in the damaged blade does have some small contribution towards the split in repeated modal frequencies.

Due to the boundary conditions of the models, a “free” mode was observed, allowing for rotation of the blisk around the central hub section in a spinning motion. Although the lack of fixation in the rotational-Z direction was present, modes were still found to be accurate and reliable when compared with experimental values. This compression-only support boundary condition also matches the actual test rig. Locking the blisk in the rotational-Z direction within the experimental fixture should be considered for future testing.

Conclusions

The process of validation presented allowed for several conclusions regarding the system to be made:

1. Closely relating model boundary conditions to the TWS blisk fixture allows for much more accurate FE predictions on modal frequencies.
2. Repeatable experimental modal analyses using a scanning laser vibrometer as the measurement tool was achieved.
3. The TWS was shown to be sensitive enough to detect small amounts of mistuning due to simulated FOD.
4. Comparison between the two cases examined show that a maximum of 2% difference in natural frequencies is present for the research blisk. As the system is sensitive enough to detect such a small change; the system can be considered validated for use to the more complex structure of a real blisk.

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