

Australian Government

**Department of Defence** Science and Technology

# Travelling Wave Excitation System Verification through Mistuned Blisk Analysis

Mitchell Cosmo, Jianfu Hou and Marco Attia

Aerospace Division Defence Science and Technology Group

#### DST-Group-TR-3568

#### ABSTRACT

An acoustic travelling wave system (TWS) was verified through direct comparison of numerical and experimental results of a tuned and mistuned research blisk (integrally bladed rotor). The system, developed by the Defence Science and Technology (DST) Group, is used for characterising mistuning of blisks, which can contribute to premature High Cycle Fatigue (HCF) failures in gas turbine engines fitted in modern military aircraft. The finite element method (FEM) was applied and a modal analysis was conducted to determine numerical values of which to compare to experimental data obtained from TWS tests. A 12-bladed, flat, stainless steel research blisk was analysed using the TWS, with results showing promise with less than two percent error through comparison of modes (natural frequencies) of the two blisk cases examined. System improvements, limitations and possible sources of error are also discussed within this report.

**RELEASE LIMITATION** *Approved for public release.* 

Produced by

Aerospace Division 506 Lorimer Street Fishermans Bend VIC 3207

*Telephone:* 1300 333 362

© Commonwealth of Australia 2019 February 2019

## APPROVED FOR PUBLIC RELEASE.

# Travelling Wave Excitation System Verification through Mistuned Blisk Analysis

# **Executive Summary**

Due to the wide use of integrally bladed disks (blisks) in modern gas turbine engines for lighter weight and higher performance, High Cycle Fatigue (HCF) increasingly becomes a cost and safety driver. It is important to be able to understand the behaviour of blisks, particularly mistuning caused by variations of material or geometric properties between blades – which contributes to premature HCF failures.

A travelling wave system (TWS) is one of methods for testing the vibration modes (resonant frequencies) of blisks in order to characterise mistuning. TWS testing is generally simple and low in cost, in comparison to traditional spin testing, that provides a non-contact solution replacing strain gauges which may otherwise change the dynamic response of a blisk. Therefore, the Defence Science and Technology (DST) Group have developed a TWS to enhance its capability in this field.

A finite element analysis (FEA) was applied using ANSYS 17.1 to analyse the differences between tuned and foreign object damaged (FOD) research blisks. FOD was examined due to its occurrence in aircraft engines and has direct relevance to mistuning. Three 3D CAD models were produced with different locations of damage in each modelled blisk in order to examine the worst-case-scenario of FOD.

Experimental work was undertaken using the TWS with multiple repeated tests for each engine order (EO). Modes extracted from the FEA were compared with those from the experimental analyses for the tuned and mistuned blisk case in order to assess the system. Mode matching for both sets of results ensured that the mode frequencies were properly correlated. It was determined that there was less than two percent error between numerical predictions and experimentation; proving the system is usable for real inservice blisks.

Outputs determined allow DST to enhance capability to provide independent airworthiness advice to the Australia Defence Force (ADF) concerning HCF and HCF-related failures. The verified TWS allows for testing of real, in-service blisks to contribute to the reduction of HCF-related events in aircraft engines.

*This page is intentionally blank.* 

# Authors

## Mitchell Cosmo

Aerospace Division

Mr Mitchell Cosmo joined the Defence Science and Technology Group in 2015 as a Cadet. He graduated from Griffith University in 2016 with a Bachelor of Engineering (Mechanical), awarded with the Griffith University Medal for Academic Excellence. Since then, he has contributed to the development of DST's HCF capabilities within the Engine and Fuels Integrity group of the Aircraft Health and Sustainment Branch of Aerospace Division. Mitchell's current focus is on finite element analysis of blisk structures.

## **Jianfu Hou** Aerospace Division

Dr Jianfu Hou joined (then) DSTO in 1998 after receiving a PhD in Mechanical Engineering from the Royal Melbourne Institute of Technologyin 1995. Presently, he is a Senior Defence Scientist and S&T Discipline Lead for engine life assessment in Aerospace Division. As well as being responsible for planning and implementing the research program in engine lifing, his research interests include FE analyses for gas turbine engine components, life prediction and crack growth modeling, rotor dynamics and bladed disk vibration, design optimisation, fatigue life prediction and impact simulation.

## Marco Attia Aerospace Division

Mr Marco Attia is a Propulsion Systems Engineer currently working in the Engine and Fuels Integrity Group within the Aircraft Health and Sustainment Branch of the Aerospace Division. Marco completed his Bachelor degree (Honours) in Aerospace Engineering from the Royal Melbourne Institute of Technology in 2005. Since joining DST Group in 2007, Marco has been involved in a wide range of projects within the propulsion stream. His major disciplines of work include gas turbine performance modelling, finite element analysis, materials research for high temperature applications, and more recently cyclic spin testing. Since 2015, Marco has focussed his attention on developing a high cycle fatigue spin testing capability at the DST Group.

*This page is intentionally blank.* 

# Contents

1.	INTI	RODUCTION1
	1.1	Background 1
	1.2	Objectives
2.	THE	TRAVELLING WAVE SYSTEM
	2.1	System Configuration
	2.2	The Research Blisk
		2.2.1 Tuned Case
		2.2.2 Mistuned Case
	2.3	Recent System Developments
	_,,,	
3	NILIN	AFRICAL METHODS 8
0.	31	CAD Modelling 8
	0.1	311 Baseline CAD Model 8
		3.1.2 EOD Modelling
	2 7	5.1.2 FOD Modeling
	5.2	Thine Element would Analysis
1	EVDI	EDIMENITAL INVESTIGATION 12
4.	елгі 4 1	ENTIVIENTAL IN VESTIGATION
	4.1	Frocedures
	4.2	Experimental Testing 15
_	DECI	
5.	RES	ULTS
	5.1	Numerical Results
	5.2	Experimental Results
	5.3	Results Comparison
		5.3.1 Tuned Case 19
		5.3.2 Mistuned Case
	5.4	Engine Order Examination 23
6.	DISC	26 CUSSION
7.	CON	ICLUSION
	7.1	Future Work 28
8.	REFI	ERENCES 29
<u>ـ</u>		
AI	PPENI	DIX A EXPERIMENTAL RESULTS

DST-Group-TR-3568

*This page is intentionally blank.* 

# 1. Introduction

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) as a compressor.

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 effect 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. However, this system requires verification of its usage before being applied to today's in-service blisks.

## 1.1 Background

Whereas traditional rotors are made up of a blade and disk subassembly, blisks are by design, a single piece of material made up of both the blades and disk. As a single piece, these types of rotors alone can increase the efficiency of an engine up to 8% in some cases [1]. In addition, the lack of any major joins also reduces the probability of crack initiation and/or propagation at the blade roots. Although there are many advantages to using blisks in aircraft engines, they are highly susceptible to HCF due to their lack of any natural damping, resulting in large resonant vibration throughout the component; which can be significantly worse for a mistuned blisk. Mistuning changes the original design specifications of the blisk and even small differences between blades can cause unintended high amplitude vibrations and stress in the blades which can occur in only one or few blades (termed localisation [2]). The stresses in these regions thus contribute to the onset of HCF.

In order to detect the extent of mistuning for a particular blisk; it is possible 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 which has the advantage of much lesser cost than traditional spin testing. These types of systems can utilise either magnetic or acoustic excitation to excite a blisk. Non-contact test devices are commonly tied with a scanning laser vibrometer for data acquisition and visualisation of the vibration modes and mode shapes without using strain gauges, which may otherwise change the blisk's dynamic response.

Since HCF is one of the critical issues being faced by today's gas turbine engines; it is imperative to develop and enhance DST's current capability in order to provide independent airworthiness advice to the Australian Defence Force (ADF). A major contributing factor towards DST's HCF capability is to support Australia's acquisition of the F-35 (Joint Strike Fighter (JSF)); of which there have been several failure events to date. The TWS has the capacity to support this venture through verification of blisks following foreign object damage (FOD)/domestic object damage (DOD) repair. To date, the issues

related to the certification of blisk repair and blending has not been addressed by the Joint Program Office (JPO) or Original Equipment Manufacturer (OEM).

Significant work has been completed by the authors regarding the TWS located at DST Fishermans Bend [10, 11], however there have been recent developments which has changed some outcomes. This report outlines the changes made to the system from information outlined in [11], and the most up-to-date methods and results gathered through research blick testing in order to substantiate the system's usage into the future.

## 1.2 Objectives

The main objective of this work was to verify the usage of the travelling wave system on a tuned and mistuned research blisk.

The following objectives were set in order to advance development of the TWS:

- 1. Generate two 3D CAD models of the research blisk (one baseline and one with applied damage). The damaged model was to simulate damage caused by foreign-object ingestion through an engine.
- 2. Model different locations and size of damage for the mistuned blisk and determine the worst-case scenario using finite element analysis (FEA).
- 3. Perform reliable finite element models of both research blisk models. The finite element method (FEM) was to be applied through a Modal Analysis.
- 4. Extraction of modes and mode shapes of the two physical blisks (one with applied damage determined from the FEA) using the TWS and Polytec Scanning Laser Vibrometer (SLV). Modes will be examined over several engine orders (EOs).
- 5. Troubleshoot and evaluate the TWS to eliminate or reduce errors present within the system as a whole. Inclusive of the SLV and speaker subsystems.
- 6. Compare results from both FEA and experimental analysis and make reasonable assumptions and engineering judgement as to the viability of the TWS for use on real engine blisks.

This report aims to outline the completion of the research objectives whilst also discussing certain limitations uncovered throughout experimentation.

# 2. The Travelling Wave System

The travelling wave system developed by DST uses an acoustic signal to excite a blisk mounted on a fixture. Such a system excludes the centrifugal loads which would normally be present within a gas turbine engine, focussing directly on gathering vibratory load data. Although centrifugal loading is an important factor in HCF analysis for blisks, oil jet spintest setups are usually much more expensive and complex. In a real engine, vibratory loads are caused by the gas flow fluctuations associated with the number of vanes or stators up- or down-stream from the rotor – commonly referred to as engine order excitation. In order to express this type of excitation to the blisk, the TWS applies harmonic excitation to all the blades with the same vibration amplitude but at differing phase angles. It is possible to express the excitation forcing function as:

$$F_i = F_0 \sin(\omega t + i\theta) \tag{1}$$

$$\theta = \frac{2\pi E}{n} \tag{2}$$

And  $F_i$  is the force applied to each of the blades,  $F_0$  is the force amplitude,  $\omega$  is the excitation frequency, *t* is the time, *i* is the blade number,  $\theta$  is the phase difference, *E* is the engine order number and *n* is the total number of blades on the blick. For the travelling wave system, the excitation frequency corresponds to the rotational speed of the engine. The system outlined in this report is the same described in [11], with minor changes and fixes which are stated under section 2.3 of this report.

## 2.1 System Configuration

The TWS is comprised of three main sub-systems; the excitation sub-system, blisk fixture sub-system and the data acquisition sub-system – as shown in Figure 1. Each sub-system must work together in order to provide accurate and reliable results; the schematic of which is shown in Figure 2.

The excitation sub-system consists of a function generator (in the form of a touch screen graphical user interface (GUI)) to produce the requested amplitudes, frequencies and phase angles desired by the user. 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. This setup allowed for the correct frequencies and phases associated with a particular engine order excitation.

The blisk fixture is mounted on a Kinetic Systems Vibraplane vibration-resistant 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 mounted to the rear of the fixture wired directly to the amplifiers via 2-channel inputs. The output from the speakers was then delivered to the blisk through PVC tubing.

DST-Group-TR-3568

A scanning laser vibrometer developed by Polytec was used as the measurement tool for vibrations of the blisk. Hardware from Polytec 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.



Figure 1. Travelling Wave Excitation System Setup [11]



Figure 2. Schematic of TWS setup showing relevant sub-systems and important components [11]

## 2.2 The Research Blisk

The research blisk provides a baseline for the travelling wave system testing to reduce any significant errors that may be present in a real blisk structure. The blisk was designed by DST and represents the dynamic properties of the T700 1<sup>st</sup> stage blisk. Several of these identical blisks were manufactured using a laser manufacturing process from a single piece of stainless steel sheet. These pieces were designed to be simple in design and thus easy to manufacture and mount. There were two cases considered within the experiment conducted in this report; a tuned case where no damage was present, and a mistuned case which had significant damage on one of the blades.

### 2.2.1 Tuned Case

The tuned case allowed for a baseline examination of the blisk. It was noted in [10] that there was some damage along some blades due to the laser cutting process, however this small mistuning was neglected due to the insensitivity of the blisk. A photograph of the tuned case is shown in Figure 3 mounted on the TWS fixture.



Figure 3. Undamaged (tuned) research blisk used in experimental testing

### 2.2.2 Mistuned Case

Mistuning of the blisk required a location and size for a "worst-case-scenario" damage. The damage to be applied to the blisk was designed to simulate a foreign object damage strike to the blade – a common occurrence on 1<sup>st</sup> stage blisks, and an area of interest regarding blending repair limits. Prior finite element analysis completed [12] proved that mid-span of the blade increased vibration amplitudes in a blisk the greatest. This location for damage was confirmed when a simplified finite element analysis was performed. The

damage was created through the use of EDM by taking a datum from the blade tip. A photograph of an example mistuned blisk is seen in Figure 4.



*Figure 4.* Damaged (mistuned) blisk used in experimental testing. FOD present on blade number one, surrounded in red.

## 2.3 Recent System Developments

Previous experimentation and reports had proved the usefulness of the TWS for blisk HCF testing; however there were errors present that were unidentified. As such, an investigation was undertaken to inspect the phase shifter (function generator) for the correct phase between differing channels. An oscilloscope was used to determine the signal output from multiple different sets of channels with selections within the GUI differing between separate tests.

Testing was conducted using the first four channels from the output side of the function generator and were assumed that these channels should have the set phase angle between them. Oscilloscope readings showed that each of the four channels were the same in both phase and amplitude. The fourth and fifth channels however did show a phase change. It was discovered from these tests that the I/O card from the phase shifter had the same output for all four signals attached to that card; therefore a fix was sought from on-site technical staff. A software glitch was discovered within the function generator code and a fix was implemented in March, 2017. Testing since resolving this issue shows the correct phase differences between channels and data acquisition reveals result data with less noise across the averaged frequency spectrum.

Additionally, some minor alterations have been made from March, 2017 in order to reduce noise and increase the forced response of the blisk, as follows:

• Resoldering of wire from speakers to amplifiers as some contacts were insufficient.

- Properly sealing PVC hose from speakers to nozzles to maintain more pressure and hence exhibit stronger forces onto the blisk.
- Change of some Polytec system settings to better reflect and acquire data, including the addition of an "FFTExt" software option which allows the system to analyse up to 819 200 FFT lines.
- Necessary air pressures for the vibration-resistant table have now been set; previously this system was idle.

Since these changes have been made, clearer results have become evident. This then allows for further development of the system beginning with an "upgrade" to the blisk fixture. The fixture allows for a current in-service blisk to be fitted, analysed and reported in 2018.

# 3. Numerical Methods

The Finite Element Method (FEM) was employed for the current research in order to confirm the worst-case location of damage along a blade for the research blisk and also perform the relevant modal analyses for later comparison with experimental results. Numerical results obtained from FE analysis are used to verify the TWS through comparison of the experimental modes and mode shapes.

## 3.1 CAD Modelling

Computer-Aided Design (CAD) models were created using SolidWorks to be used in a FEA. A total of four models were designed – one perfectly tuned, and three which were used to determine the worst location of damage. The perfectly tuned blisk model was designed firstly using a reverse-engineering approach; by the use of accurate measurements of the already-produced tuned research blisk. From these measurements, it was possible to generate a solid model.

### 3.1.1 Baseline CAD Model

The baseline model shown in Figure 5 has a simple design with a completely symmetrical 12-bladed structure. No attempts were made to model the physical blisk's minor defects.



Figure 5. Perfectly tuned CAD model of the research blisk used for FEA

## 3.1.2 FOD Modelling

Three of the mistuned models each exhibited a different location of damage (of the same size) along a blade with the same size of damage; 1) the blade tip (Figure 6); 2) mid-span of the blade (Figure 7), and; 3) blade root (Figure 8). These models were used to confirm the worst location for damage to occur along a blade. Positions of the damage were placed

arbitrarily with the exception of the mid-span damage which was located centrally on the blade. The exact locations in relation to the centre of the blisk are found in Table 1 and show that the x-axis location is the same due to the damage being placed on the same edge of the same blade for consistency.

The damaged models were designed so that the damage size was large enough in order to exhibit large differences in the response from the baseline blisk. It was suggested in [13] that a V-shaped notch applied to the edge of a blade provides a good estimation of foreign object damage. The damage applied was approximated as a square rotated 45° of 8 mm radius (5.66 mm side length).

Preliminary results prior to a mesh convergence study found that damage located midspan of the blade exhibited the largest change in natural frequencies, thus confirming the results from previous studies.

Table 1.	Damage locations with	respect to the blisk orig	in (exact centre of s	ymmetric structure)
		1 0		, , , , , , , , , , , , , , , , , , , ,

	Blade Tip	Mid-span	Blade Root
x-axis location (mm)		9.75	
y-axis location (mm)	83.12	62.20	45.67



Figure 6. Top half segment of blisk model – blade tip damage



#### DST-Group-TR-3568





*Figure 8.* Top half segment of blisk model – blade root damage

## 3.2 Finite Element Modal Analysis

A modal analysis was performed in ANSYS 17.1 Workbench to determine the natural frequencies and mode shapes of the tuned and mistuned research blisk models. The analysis extracts modes dependent upon the extraction method and the existing boundary conditions (including pre-stressed effects). Modal analyses performed in ANSYS are a linear analysis and as such do not account for plasticity or contact of any defined elements. Both Young's modulus and density are defined material properties in order to successfully solve the mathematical model.

In order to conduct the FEA, the 3D CAD model was firstly brought into ANSYS 17.1 Workbench as a geometry file from SolidWorks. Geometry was edited in Workbench (SpaceClaim) to ensure correct dimensions and to apply necessary points for boundary conditions. Material properties for stainless steel were imported from engineering data to the analysis with a Young's modulus of 193 GPa, a density of 8000 kg/m<sup>3</sup> and a Poisson's ratio of 0.31. Material properties are estimated to be the average values for the grade of stainless steel used to manufacture the blisks.

Meshing was completed with the inbuilt meshing tool with a reasonably fine, uniform, quad mesh along each blade and a mapped mesh along all straight-edged faces. The central hub section was meshed using a mixture of quad and tri elements. Mesh convergence was achieved with 38 860 elements for the tuned model and 38 175 elements for the damaged case. A mapped face mesh was used for the inner hub of the blick at the location of boundary conditions. Metrics showed reasonable values for element quality, orthogonal quality and skewness.

A force was applied at the central hub of the blisk (Figure 11) which simulates the downward pressure of the torqued bolt on the experimental test rig. This force was calculated using:

$$F = \frac{T}{D_M \times \mu} \tag{3}$$

Where *F* is the force applied (N), *T* is the bolt torque (Nm),  $D_M$  is the major diameter of the bolt (m) and  $\mu$  is the coefficient of friction. At the opposite side of the blisk, a compression-only support boundary condition 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.

The static structural solution was then determined using the Mechanical APDL direct solver, followed by the modal analysis (direct solver, Block Lanczos extraction method). 26 total modes were extracted from the structure for both the tuned and mistuned case. The first and 14<sup>th</sup> modes extracted 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 set up 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. Final numerical results can be found within Section 5 of this report.



Figure 11. Tuned research blisk with bolt force boundary condition shown in red

# 4. Experimental Investigation

Two blisks were examined experimentally in order to extract the modes of baseline and mistuned models. Testing of the blisks was completed through experimental modal analysis; a very common technique in structural engineering in order to study a system's dynamic properties in the frequency domain. Typically, these types of systems use electromagnetic shakers to excite a body with a transducer feeding the data to a PC for analysis.

The system designed by DST allows the TWS to excite the blisk in the same manner of the shakers without any physical contact, which may otherwise change the dynamic properties. The laser vibrometer used with the system allows for non-contact data acquisition and an accompanying PC and software to analyse the results.

## 4.1 Procedures

Consistent results were required throughout the study to ensure comparisons were made without excess system errors. All engine orders were simulated using the TWS using the following steps:

- 1. The blisk was installed onto the mounting plate and tightened to a 30.5 Nm torque. This same torque was applied to the damaged and undamaged blisks.
- 2. Gap size (perpendicular distance from the blade to the nozzle) was set at 0.127-0.2032 mm (0.005-0.008 inch). This distance allowed for nozzle vibration without contact with the nozzle.
- 3. Data acquisition equipment was powered on. It was necessary to wait for the system to adjust to lighting, allow the laser to "warm-up", and start the PSV software.
- 4. A scan point grid was created for each blisk which would fit the two dimensional shape of the blisk. An example of which is shown in Figure 12. The scan points were necessary to examine the average frequency spectrum across the entire blisk while also providing mode shape analysis.
- 5. The necessary settings for the SLV were checked to retrieve the desired results. A summary of these settings can be found in Table 2.
- 6. The TWS and associated amplifiers were turned on and checked.
- 7. Settings for the TWS were then entered on the GUI ensuring the sweep function was set to "on". These values are found within Table 3.
- 8. Phase offset was calculated using equation 2 and set in units of degrees (°) for each EO examined.
- 9. The TWS was initialised to begin output through the speakers in order to excite the blisk(s). It was important to ensure adequate hearing protection (class 5+) was worn to prevent hearing damage.

- 10. The SLV was started on the software. Tests are completed automatically by scanning the individual points set in the software. These test scans can vary in time to complete.
- 11. Once scanning was completed, the TWS was turned off through the "output enable" button on the GUI.

This procedure was followed for both blisks (damaged and undamaged). Both average frequency spectrum (FFT) and mode shape animations were taken from the PC by use of the export function.



Figure 12. Scan points set for the damaged research blisk within the PSV software

### DST-Group-TR-3568

Tab	Setting	Selection	Notes
General	Measurement Mode	FFT	Fast Fourier Transform measurements.
	Averaging	Complex (3)	Complex averaging over 3 individual point scans.
	Remeasure	On	Allows invalid scan points to be remeasured.
Channels	Vibrometer	Active	Direction = $+Z$ , Range = $10V$ ,
	Reference 1	Active	Coupling = DC
Filters	Bandwidth	1.25 kHz	Total scan bandwidth.
	From	0.65 kHz	Lower scan range.
	То	1.25 kHz	Upper scan range.
	FFT Lines	6400	Number of FFT lines necessary to scan this bandwidth and range.
	Overlap	0%	Percentage of interpolation between scan points.
Window	Vibrometer	Hanning	Use of the Hanning window
	Reference 1	Hanning	type for both inputs.
Trigger	Source	Off	No trigger was used.
SE	Speckle Tracking	On	Improves signal when laser light is scattered. Set to "Fast".
Vibrometer	Velocity	VD-04 10 mm/s/V	Velocity scan head type.
	Tracking Filter	Off	
	Low Pass Filter	Off	Not requirea.
	High Pass Filter	100 Hz	Removes lower frequency electrical noise.

Table 2.	Polytec Scanning	Laser	Vibrometer	software	settings.	Settings we	re identical	for	each
	blisk examined								

Table 3.	TWS settings	for all	experiments	conducted
----------	--------------	---------	-------------	-----------

Amplitude (%)	Start Frequency (Hz)	End Frequency (Hz)	Sweep Time (s)
100	650	1250	30

## 4.2 Experimental Testing

The experimental testing included both blisks with improvements made to the TWS which were suggested under heading 2.3. Each EO was tested in order to make an assessment on the verification of the system. The information outlined in Table 4 describes the tests that were undertaken including the relevant phase offset input to the TWS for individual scans. Note that for each scan number described, tests were completed three times. Each dataset for these tests were averaged for single data point amplitudes. 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 without use of a trigger for the 12-bladed research blisk described. The results of experimental testing can be found within section 5 of this report.

Scan Number	Blisk	Engine Order	Phase Offset (°)
1		1	30
2		2	60
3		3	90
4		4	120
5		5	150
6	Undamaged	6	180
7	(Tuned)	7	210
8		8	240
9		9	270
10		10	300
11		11	330
12		12	0
13		1	30
14		2	60
15		3	90
16		4	120
17		5	150
18	Damaged	6	180
19	(Mistuned)	7	210
20		8	240
21		9	270
22		10	300
23		11	330
24		12	0

Table 4. TWS settings for all experiments conducted

# 5. Results

Results for the current study are reported in the subsequent sections. Numerical results will be outlined first, followed by those determined experimentally. A comparison is then made to determine suitability of the TWS for future use.

### 5.1 Numerical Results

Table 5 shows the first 12 relevant modes obtained from the pre-stressed modal analysis of the tuned and mistuned blisks. The results from the FEA show that the mistuned blisk exhibits only a very minor difference in response from the tuned case. The small frequency difference can be attributed to the robustness of the research blisk design. It is evident however that each repeated mode (No. 2, 5, 7, 9 and 11) is higher in frequency for the mistuned case compared with the undamaged case. This relates to the unsymmetrical geometry of the damaged blisk.

The mode shapes for each mode for the tuned case can be found in Figure 13. The mistuned case did not show any major differences in mode shapes in comparison with the undamaged blisk. Extraction of the mode shapes allows for direct comparison with experimental results, whilst also giving further insight into dynamic properties of the blisk. Each mode shape is shown on a scale of total deformation; however, as deformation size is unrealistic in an ANSYS Mechanical Modal Analysis, scale has been excluded.

Mada Neurobar	Mode Freq	Difference (Uz)	
Mode Number	Tuned Case	Mistuned Case	Difference (HZ)
1	725.43	725.44	-0.01
2	725.44	725.99	-0.55
3	775.52	775.79	-0.27
4	809.78	809.78	-0.00
5	809.79	810.33	-0.54
6	971.51	971.50	-0.01
7	971.52	971.91	-0.39
8	1084.74	1084.72	0.02
9	1084.75	1084.96	-0.21
10	1141.21	1141.20	0.01
11	1141.21	1141.29	-0.08
12	1158.07	1158.09	-0.02

Table 5. Summarised natural frequencies for the two blisk cases examined numerically

#### DST-Group-TR-3568



Figure 13. Mode shapes of the tuned research blisk from ANSYS Mechanical

## 5.2 Experimental Results

The experimental results obtained from the Polytec system are found in Table 6 for the modes discovered between 650-1250 Hz. As expected from the numerical analysis, the first family was found within this range. Five tests were conducted for each blisk at EO1 to prove repeatability; however as there were minor changes between each test, an average frequency was taken to find a representative mode. The mean and standard deviation was calculated for each mode, with a greatest standard deviation of 4.2 Hz at the 1<sup>st</sup> mode. There was a much larger difference between the tuned and mistuned cases for experimental modal analysis than what was predicted numerically. It is interesting to note that while the higher-frequency modes match that of the numerical predictions, the 1<sup>st</sup>, 2<sup>nd</sup> and 5<sup>th</sup> modes actually have a lower frequency.

Mode shapes were taken directly as images from the Polytec software and are displayed in Figure 14. Due to the multiple repeated modes extracted, mode shapes are also repeated. Once again, there were no major distinctions between mode shapes of the tuned and mistuned cases. Nodal diameters for each image were easily determined through animation of the mode shapes within Polytec PSV Software (not evident in images).

Mada Numbar	Mode Freq	Mode Frequency (Hz)		
Mode Number	Tuned Case	Mistuned Case	Difference (HZ)	
1	720.07	701 (	7.07	
2	/38.8/	731.6	1.27	
3	765.59	762.85	2.74	
4	810.35	813.20	-2.85	
5	816.21	813.28	2.93	
6	070 01		0.07	
7	972.81	975.08	-2.27	
8	1000 44	1004.05	1 41	
9	1083.44	1084.85	-1.41	
10	1132.50	1134.88	-2.38	
11	1143.77	1145.78	-2.01	
12	1155.27	1157.38	-2.11	

Table 6. Natural frequencies obtained experimentally for each blisk case

#### DST-Group-TR-3568



10th mode (5 ND)11th mode (5 ND, 90° rotation)12th mode (6 ND)Figure 14. Mode shapes of the tuned research blisk from experimental modal analysis

## 5.3 Results Comparison

In this section, the two sets of results will be compared between experimental and numerical analyses in order to determine if the system meets the necessary requirements. The tuned case and mistuned case were examined separately.

### 5.3.1 Tuned Case

Comparison of the tuned (undamaged) research blisk involved overlaying the numerical results onto the FFT plot obtained from experimental data in Figure 15. 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. In order to better compare the results, Table 7 determines the percentage difference between the two sets of results.

Results show good correlation between the numerical and experimental values; with only a maximum error of < 2%. As the TWS is a completely non-contact system, this error is reasonable.



**Tuned Case Numerical and Experimental Comparison** 

*Figure 15. FFT plot of experimental data overlayed with FEA modal frequencies for the undamaged research blisk* 

Mada Nambar	Mode Freq	Percentage	
Mode Number	Numerical	Experimental	Difference (%)
1	725.43	729.97	1.82
2	725.44	/38.8/	1.82
3	775.52	765.59	-1.30
4	809.78	810.35	0.07
5	809.79	816.21	0.79
6	971.51	072 91	0.13
7	971.52	972.81	0.13
8	1084.74	1092 44	-0.12
9	1084.75	1085.44	-0.12
10	1141.21	1132.50	-0.77
11	1141.21	1143.77	0.22
12	1158.07	1155.27	-0.24

 Table 7.
 Mode comparison and percentage difference for the undamaged research blisk

## 5.3.2 Mistuned Case

Figure 16 shows the FFT plot with overlayed FE predictions for the damaged research blisk. Results obtained are also summarised within Table 8. Results for the mistuned case also show good correlation with numerical values; with a maximum error of < 2%, much like the tuned case. Although the research blisk is very robust in its design; differences between modal frequencies can be observed with minimal error.

It is evident that the first and second modes have less error percentage than the tuned case when comparing numerical and experimental results. Split repeated modes (mode numbers 2, 5, 7, 9 and 11) are, in general, more accurate than their baseline counterpart. These observations show that the TWS can detect slight changes in the research blisk's dynamic response.

DST-Group-TR-3568



Mistuned Case Numerical and Experimental Comparison

*Figure 16. FFT plot of experimental data overlayed with FEA modal frequencies for the damaged research blisk* 

Mada Number	Mode Freq	Percentage			
Wode Number	Numerical	Experimental	Difference (%)		
1	725.44	721 (0	0.84		
2	725.99	/31.60	0.77		
3	775.79	762.85	-1.70		
4	809.78	813.20	0.42		
5	810.33	813.28	0.36		
6	971.50		0.37		
7	971.91	975.08	0.33		
8	1084.72	1004.05	0.01		
9	1084.96	1084.85	-0.01		
10	1141.20	1134.88	-0.56		
11	1141.29	1145.78	0.39		
12	1158.09	1157.38	-0.06		

 Table 8.
 Mode comparison and percentage difference for the damaged research blisk

### 5.4 Engine Order Examination

In addition to the previously outlined results, an engine order examination was undertaken experimentally. A simplified testing condition was performed which included only a single scan point per blade through PSV software. The aim of this testing was to determine the effects of engine order (EO) on dynamic response of the research blisk. Examination of EO effects allows for further verification of the TWS through a real engine condition. Figures 17-21 outline the most significant responses in the form of an FFT plot, with the remainder of results contained within Appendix A.

From the figures below, it is evident that specific engine orders excite individual modes greater than others, thus increasing amplitudes. As an example, Figure 17 gives an FFT plot of an averaged EO3 test with the ~975 Hz (number 6 & 7) mode of much higher amplitude with respect to the others. Following this experiment, the EO4 test was conducted (Figure 18), which shows the "next set" of modes (8 and 9) or ~1084 Hz at higher amplitude respective of the others. This trend continues for EO5 (Figure 19) and EO6 (Figure 20) with the 10<sup>th</sup> and 11<sup>th</sup>, and 12<sup>th</sup> mode highly excited respectively. Examination of EO7 (Figure 21) then continues the trend, however in reverse, as the 10<sup>th</sup> and 11<sup>th</sup> modes are once again more excited than other modes in the plot. These observations are interesting to note as it was the case for both the tuned and mistuned case.



**Research Blisk Experimental FFT Results for Engine Order 3** 

Figure 17. Experimental data obtained from an EO3 TWS test for both tuned and mistuned cases

DST-Group-TR-3568



**Research Blisk Experimental FFT Results for Engine Order 4** 

Figure 18. Experimental data obtained from an EO4 TWS test for both tuned and mistuned cases



**Research Blisk Experimental FFT Results for Engine Order 5** 

Figure 19. Experimental data obtained from an EO5 TWS test for both tuned and mistuned cases



**Research Blisk Experimental FFT Results for Engine Order 6** 

Figure 20. Experimental data obtained from an EO6 TWS test for both tuned and mistuned cases



**Research Blisk Experimental FFT Results for Engine Order 7** 

Figure 21. Experimental data obtained from an EO7 TWS test for both tuned and mistuned cases

## 6. Discussion

The research blisk was found to be highly robust in its design, as proven by the small differences in numerical results for both tuned and mistuned cases. A maximum frequency difference of -0.55 Hz for the second mode was determined through a FEA; much less than the experimental test cases. Due to the marginal change, the experimental error presented is significant in relation to FE predictions. However, proof of the geometric differences between the two blisk cases is evident in the FEA through the increase in frequency of the secondary repeated modes of the first family. 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 damage blade does have some small contribution towards the split in repeated modal frequencies.

New FE predictions are shown to be much more accurate than results from previous reports, with a maximum error less than 2%. These results show that the introduction of the force boundary condition where the experimental blisk is mounted to the fixture does introduce a local stiffening effect; decreasing the lower-frequency modes in order to relate more closely with those observed experimentally. 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. A contact between the rear of the blisk and the fixture should be considered for future FEA.

Errors present within the experimental results were also considered. The major concern relating to the method of experimental testing described in this report is that the system is completely non-contact. As sound waves are projected onto the blisk, error may be introduced in the form of external noises internal or external to the test facility, soundwave reflection, or large vibrations from other onsite sources. For the latter case, the vibration-resistant table aims to reduce these large vibrations. However, the many number of tests undertaken throughout experimentation with little-to-no deviation in modal frequency proves these issues are insignificant. The measurement tool (Polytec Scanning Laser Vibrometer) also introduces some small error, although the accuracy of measurement is high for the purposes of this project. TWS tests can be stated to be highly repeatable as there are no significant issues across all tests conducted.

Blisk manufacture was completed through a laser cutting process, introducing a heat affected zone at the surface of the structure. Due to this process, stiffness and density of the stainless steel may be inconsistent throughout the thickness of the research blisk, which may explain the large split of modes 10 and 11 in both tuned and mistuned experimental analysis (shown clearly in Figure 15 and 16). As the tuned case shows this mode-split, the material itself, or the processes used to manufacture the blisk may have introduced some irregularities.

It is possible that some blisk modes may be affected by the natural frequency vibrations of the blisk fixture or PVC tubing connecting the speakers and nozzles of the TWS. It is

difficult to assess these problems, however, as the modes are assumed to be low in frequency; likelihood of mode interaction is small. The SLV may be used in future testing in order to determine whether fixture or tubing modes interact with any of the research blick modes. In addition, tools used for fixing the blick (e.g. torque wrench) must be checked and calibrated for all future testing.

It was determined in experimental testing that power from the speakers is lacking at nozzle output. Amplitudes detected through the PSV may not be reliable due to the small forces applied to the blisk. Loss of energy while sound is travelling through the speaker housing, tubing and nozzle is likely. The EO investigation does show promise in amplitude-mode association, with the majority of modes having similar amplitudes across multiple tests. Further analysis may be required through a high resolution scan of the real blisk focussed on a single mode. In doing this investigation, peak splitting may also be evident; one element missing in the current study.

Engine order testing proves the TWS's usage for multiple different EOs for many real blisks. Considering the changes between mode amplitudes in Figures 17-21 and A1-A7 with identical conditions except from EO; a direct relationship can be assumed. These results prove that the dynamic response of the blisk does change under different EOs. From the example given under heading 5.4; increasing engine orders will excite the next "set" of modes among the first family. Further analysis of the effects of EO on dynamic response will be necessary for a real blisk.

# 7. Conclusion

Experimental and numerical results obtained show a viable and highly repeatable testing system for the examination of blisks. Comparison between the two sets of results show that a maximum of two percent error is present for the research blisk examined. Outputs of this study are as follows:

- 1. Two 3D CAD models of a research blisk were developed which accurately depict a physical blisk specimen designed for baseline TWS verification. FOD was replicated on one CAD model large enough to instigate a change in dynamic response.
- 2. A preliminary FEA was conducted in order to examine the worst-case-scenario of FOD; determined to be mid-span of a blade.
- 3. FE models were found to be reliable, with boundary conditions replicating the real conditions from the TWS. Reliability was measured through a mesh convergence and checking for major errors within the model. Modes and mode shapes were extracted using a Modal Analysis in ANSYS Mechanical 17.1.
- 4. Experimental modal analysis using a Polytec Scanning Laser Vibrometer as the measurement tool was completed. Modes and mode shapes were extracted from the output data of a multiple set of tests of different EOs. It was proven that the phase shifter component of the TWS allows for testing of multiple different EOs.
- 5. The TWS was free from any significant error following the changes outlined in section 2.3.
- 6. Comparisons were made between numerical and experimental results obtained. From these data with the small amount of error over both blisks cases studied; the TWS can be considered a verified system to examine real blisks.

## 7.1 Future Work

Future finite element modelling may involve the use of contact between two surfaces of the blisk and fixture. By doing so, further damping may be introduced which may reduce numerical-experimental error further. Examination of the effects will be conducted on a real blisk as curvic couplings or shaft connections provide a much more reliable and predictable contact surface.

Real blisk testing is necessary before the TWS is used for blending repair, intentional mistuning, or additive manufacturing repair research. Therefore future work will involve FEA and experimental testing of a real, current in-service blisk.

# 8. References

1. Croft, J. *NBAA: GE TechX fan blisk is all the buzz*. (2010) [Accessed 2017 3 October]; Available from: https://www.flightglobal.com/news/articles/nbaa-ge-techx-fan-blisk-is-all-the-buzz-348755/.

2. Castanier, M. P. and Pierre, C. (2006) Modeling and Analysis of Mistuned Bladed Disk Vibration: Status and Emerging Directions. *Journal of Propulsion and Power* **22** (2) 384-396

3. Freund, O., et al. (2013) Non-contact test set-up for aeroelasticity in a rotating turbomachine combining a noval acoustic excitation system with tip timing. *Measurement Science and Technology* **25** (2014) 1-13

4. Giersch, B. B. T., Kuhhorn, A. and Nipkau, J. (2014) Forced Response Analysis of a Mistuned Compressor Blisk. *Journal of Engineering for Gas Turbines and Power* **136** 1-13

5. Giersch, T., et al. (2013) Forced Response Analysis of Mistuned Radial Inflow Turbines. *Journal of Turbomachinery* **135** 1-9

6. Holland, D. E., et al. (2010) Testing and Calibration Procedures for Mistuning Identification and Traveling Wave Excitation of Blisks. *Journal of Engineering for Gas Turbines and Power* **132** 1-9

7. Jones, K. W. and Cross, C. J. (2003) Traveling Wave Excitation System for Bladed Disks. *Journal of Propulsion and Power* **19** (1) 135-141

8. Rzadkowski, R., et al. (2011) Forced Response of the Mistuned First Stage Compressor Bladed Disc of an Aircraft Engine - Experimental and Numerical Results. In: 13th World Congress in Mechanism and Machine Science, Guanajuato, Mexico: 19-25 June

9. Stanbridge, A. B., Sever, I. A. and Ewins, D. J. (2002) Fifth International Conference on Vibration Measurements by Laser Techniques: Advances and Applications

10. Cosmo, M. (2015) *Verification of a Travelling Wave Excitation System: Experimental and Numerical Analysis of a Foreign Object Damaged Research Blisk.* Griffith University

11. Hou, J., et al. (2016) *Development of a Travelling Wave Excitation System*. Defence Science and Technology Group

12. Chen, G., et al. (2017) Evaluation of Blade Blending Induced Mistuning in an Integrally Bladed Disk. In: *ASME Turbomachinery Technical Conference & Exposition*, Charlotte, NC, USA: 26-30 June 2017

13. Witek, L. B., A. and Stachowicz, F. (2015) Fatigue analysis of compressor blade with simulated foreign object damage. *Engineering Failure Analysis* **58** (2015) 229-237

DST-Group-TR-3568

*This page is intentionally blank.* 

# Appendix A Experimental Results

## A.1 Engine Order Examination

Figures A1-A7 are supplementary experimental results for comparison of FFT plots during the engine order examination described in section 5.4.



Figure A1. Experimental data obtained from an EO1 TWS test for both tuned and mistuned cases

DST-Group-TR-3568



**Research Blisk Experimental FFT Results for Engine Order 2** 

Figure A2. Experimental data obtained from an EO2 TWS test for both tuned and mistuned cases



**Research Blisk Experimental FFT Results for Engine Order 8** 

Figure A3. Experimental data obtained from an EO8 TWS test for both tuned and mistuned cases



**Research Blisk Experimental FFT Results for Engine Order 9** 

Figure A4. Experimental data obtained from an EO9 TWS test for both tuned and mistuned cases



**Research Blisk Experimental FFT Results for Engine Order 10** 

Figure A5. Experimental data obtained from an EO10 TWS test for both tuned and mistuned cases

DST-Group-TR-3568



**Research Blisk Experimental FFT Results for Engine Order 11** 

Figure A6. Experimental data obtained from an EO11 TWS test for both tuned and mistuned cases



**Research Blisk Experimental FFT Results for Engine Order 12** 

Figure A7. Experimental data obtained from an EO12 TWS test for both tuned and mistuned cases

### DISTRIBUTION LIST

Travelling Wave Excitation System Verification through Mistuning Research Blisk Analysis

Mitchell Cosmo, Jianfu Hou and Marco Attia

### DEFENCE

### **Task Sponsor**

Sponsor Name/ Position

### S&T Program

Chief of Aerospace Division Research Leader Task Leader Head Science Team Leader Author(s)

**OTHER ORGANISATIONS** National Library of Australia

Universities and Colleges Australian Defence Force Academy

Hargrave Library, Monash University

## INTERNATIONAL DEFENCE INFORMATION CENTRES

US Defense Technical Information Center UK Dstl Knowledge Services Canada Defence Research Directorate R&D Knowledge & Information Management (DRDKIM) NZ Defence Information Centre

DEFENCE SCIENCE AND TECHNOLOGY GROUP DOCUMENT CONTROL DATA		ROUP	DLM/CAVEAT (OF DOCUMENT)
2. TITLE		3. SECURITY CLASSIFICATION (FOR UNCLASSIFIED LIMITED	
Travelling Wave Excitation System Verification Through Mistuned Blisk Analysis		Document (U) Title (U) Abstract (U)	
4. AUTHOR(S)		5. CORPORATE AUTHOR	
Mitchell Cosmo, Jianfu Hou and Marco Attia		Defence Science and Technology Group	
		506 Lorimer Street	
		Fishermans Bend Victoria 3207 Australia	
6a. DST GROUP NUMBER	6b. TYPE OF REPORT		7. DOCUMENT DATE
DST-Group-TR-3568	Technical Report		April 2018
8. OBJECTIVE ID	9.TASK NUMBER		10.TASK SPONSOR
	17-584		DASA and JSF Division
11. MSTC		12. STC	
Aircraft Health & Sustainment		Engines & Fuel Integrity	
13. DOWNGRADING/DELIMITING INSTRUCTIONS		14. RELEASE AUTHORITY	
		Chief, Aerospace Division	
15. SECONDARY RELEASE STATEMENT OF THIS DOCUMENT			
Approved for public release.			
OVERSEAS ENQUIRIES OUTSIDE STATED LIMITATIONS SHOULD BE REFERRED THROUGH DOCUMENT EXCHANGE, PO BOX 1500, EDINBURGH, SA 5111			
16. DELIBERATE ANNOUNCEMENT			
Australian Department of Defence and Defence Force Personnel.			
17. CITATION IN OTHER DOCUMENTS			
Yes			
18. RESEARCH LIBRARY THESAURUS			
Travelling wave system, high cycle fatigue, blisk, blade response, modal analysis			
19. ABSTRACT			
An acoustic travelling wave system (TWS) was verified through direct comparison of numerical and experimental testing of a tuned and mistuned research blisk (bladed disk). The system developed by the Defence Science and Technology Group (DST) is used for characterising mistuning of blisks, which can contribute to premature High Cycle Fatigue (HCF) failures in gas turbine engines fitted in modern military aircraft. The finite element method (FEM) was applied and a modal analysis was conducted to determine numerical values of which to compare to experimental data obtained from TWS tests. A 12-bladed, flat, stainless steel research blisk was analysed using the TWS, with results showing promise with less than two percent error through comparison of modes (natural frequencies) of the two blisk cases examined. System improvements, limitations and possible sources of error are also discussed			

UNCLASSIFIED

within this report.