A NOVELL TRAVELING WAVE EXCITATION MEASUREMENT TECHNIQUE

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Abstract: A traveling wave excitation system is designed to simulate engine order excitation in stationary bladed disks for the purpose of identifying forced response localization and amplification due to mistuning. The system can test bladed disks of varying sizes and number of blades using either acoustic or magnetic excitation. A new method it is presented that will reduce the signal generation costs over purchasing separate function generators or designing a phase-shifting circuit. Sources of errors in the traveling wave excitation are discussed and estimated. The novell technique of producing traveling wave excitation is demonstrated on a 23-bladed disk, and experimental forced response results are presented.

Key words: traveling wave excitation (TWE), acoustic excitation, engine order excitation (EOE), blisk.

1. INTRODUCTION

High cycle fatigue (HCF) is caused by the force applied to airfoils as they rotate through stationary disturbances in the flow field of turbine engines. This excitation is often called engine order excitation, where the engine order *C* refers to the number of equally spaced disturbances due to struts, vanes, or stators either upstream or downstream of the bladed disk. In the case of a tuned bladed disk, where all blades have the identical natural frequencies, engine order excitation causes all blades to vibrate with equal amplitudes. In the case of a mistuned bladed disk, where the natural frequencies of individual blades vary slightly, engine order excitation usually causes response localization and amplification above the tuned response, (Wie, S. T., Pierre, C., 1988, Wie, S. T., Pierre, C., 1988).

Because response amplification causes higher component stresses and contributes to HCF failures, measuring the forced response of mistuned bladed disks to engine order excitation experimentally is a great practical interest. Methods of simulating engine order excitation are especially needed to evaluate the effectiveness of intentional mistuning designs that seek to reduce the amount of response amplification due to random mistuning, (Castanier, M. P., Pierre, C., 1998).

The response of mistuned bladed disks to engine order excitation can be composed mathematically from experimentally obtained mode shapes and natural frequencies using modal analysis. However, modal testing of bladed disks can be extremely challenging due to the existence of multiple closely spaced natural frequencies, (Hollkamp, J. J., Gordon, R. W., 2001).

As an alternative, the forced response can be studied directly, either by rotating the bladed disk through stationary excitation or by rotating the excitation around the stationary bladed disk. Rotating bladed disks at realistic speeds requires complex and expensive test rigs. Therefore, it is desired to produce engine order excitation in a stationary bladed disk where standard laboratory vibration measurement device scan be used.

Kruse and Pierre carried out the first systematic experimental study of forced response amplification due to mistuning using phased piezoelectric actuators to provide traveling wave excitation to a 12-bladed disk, (Kruse, M. J., Pierre, C., 1997). This system had the disadvantage of adding a small amount of mistuning to the blades via the bonded piezoelectric actuators. Judge et al., used the same system to study the 12-bladed disk in a different frequency region.

Pierre et al., developed another traveling wave excitation system that used a number of programmable function generators to excite a 24-bladed disk with phased-acoustic excitation. This system was noncontacting, capable of any engine order excitation, and had a series of programmable gain amplifiers for calibrating the various speakers.

Slater and Bhaskar studied wave propagation in bladed disks by applying traveling wave excitation with a rotating air jet that was placed near a bladed disk, (Slater, J. C., Bhaskar, K., 1998). This excitation was noncontacting so that mistuning was not introduced, but it was limited to producing an engine order 1 excitation at rotational speeds up to 930 rpm. Another system by Slater used a rotating bladed disk placed near a stationary bladed disk to produce traveling wave excitation, (Slater, J. C., 2000). This system was also noncontacting, but was limited to engine orders of 2, 4, or 8 at rotational speeds up to 2500 rpm.

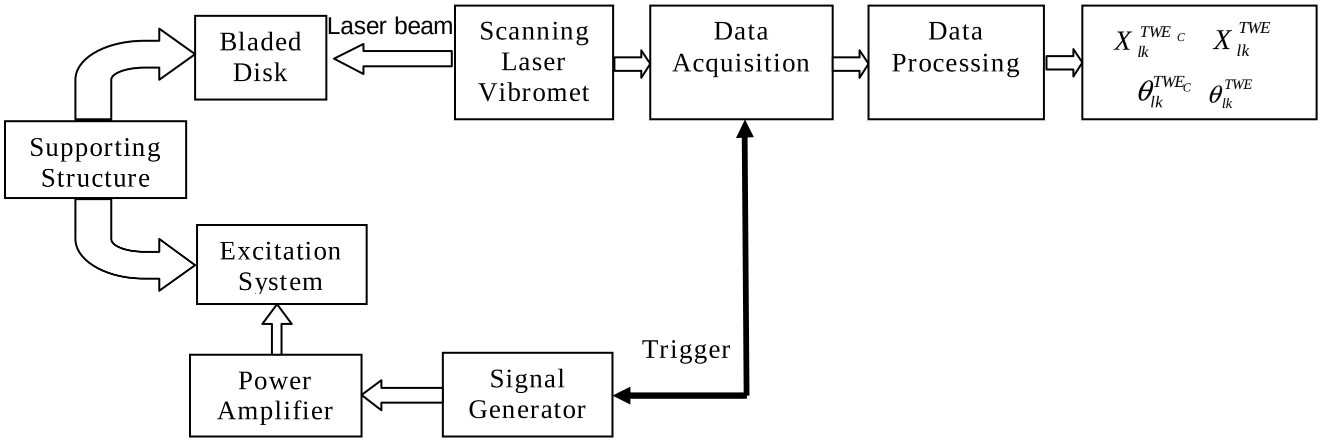


Fig. 1. Measurement experimental setup

The excitation systems of Slater excite bladed disks with phased pulses rather than the harmonically pure phased sinusoid. Although this type of excitation is a closer representation of the true HCF blade forces in a turbine engine, it complicates the correlation between experimental forced response results and analytical predictions. Therefore, traveling wave methods that provide harmonically pure sinusoidal excitation, such as those of Pierre et al., were pursued in the development of a new technique of traveling wave excitation.

2. SYSTEM DESCRIPTION

The three main components of the experimental setup are the excitation system, the measurement equipment, and a supporting structure.

The excitation consists of speakers, piezoelectric actuators, or magnets, which are placed on the opposite side of the measurement face of the blades. For traveling wave excitation and calibration, one excitation source speaker, actuator, or magnet is required behind each blade.

A laser vibrometer is used to measure vibration velocities at locations on the blade, which correspond to the nodes used in the finite element model.

The experimental setup also includes a two-axis linear traverse, a rotary table, a signal generator in conjunction with a multiplexer circuit or a PCI card for harmonically analog voltage generation, power amplifiers and a personal computer for instrument control and data acquisition as instrumentation.

Lastly, the setup includes a vibration table with custom built supports, (Judge, J. A., 2002) and mounting fixtures to hold the bladed disk and position the exciters.

A diagram of the experimental setup is shown in Fig.1.

3. SIGNAL GENERATION

A small speaker was positioned approximately at 1 mm (0.039 inch) from the rear surface of each blade. The speakers have a diameter of 10 mm and a maximum thickness of 3 mm, with an electrical impedance of 8 Ω and a maximum power of 0.3 Watts. The speakers were positioned to lie parallel to the blade faces by means of acrylic blocks cut to the same angle as the blades from the plane of the disk (as can be seen in Fig.2). Each speaker was epoxied to its own acrylic block, which was then attached with a small bolt to an acrylic plate mounted behind the test specimen.

These speakers are driven by H-P 8904 Multifunction Synthesizers in conjunction with or without a multiplexer circuit for signal comutation from one exciter to the other, depending on the single blade or traveling wave excitation that is needed to be performed. Before reaching each speaker, the output signals from H-P 8904 were conditioned by being passed through gain amplifiers, (Ewins, D. J., Han, Z. S., 1984).

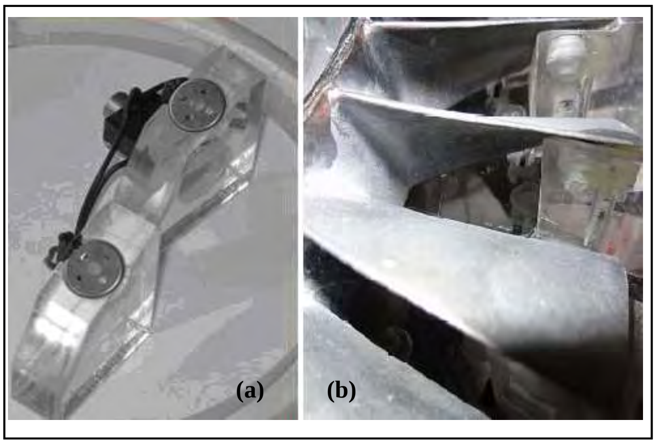


Fig. 2. (a) Speakers mounted on plastic fixtures;
(b) Speakers positioned to lie parallel to the blade faces

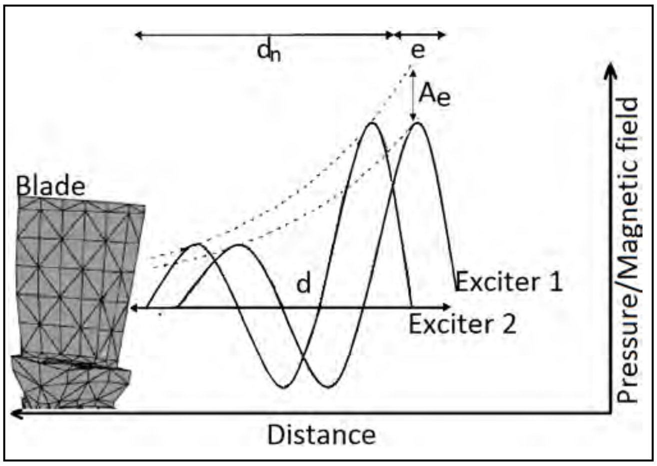


Fig. 3. Exemplification of speakers position deviation that can produce amplitude and phase errors in the excitation

4. CALIBRATION

Two types of errors are assumed to be present in the traveling wave excitation. Nonuniformity errors are caused by differences in the open-loop transfer functions of the various exciters. Position errors are amplitude and phase errors caused by varying distances between the exciters and the blades, as shown in Fig. 3.

The force amplitudes can be very sensitive to position errors. Also, note that the amplitude of the forcing varies with blade position, meaning that the forcing is slightly nonlinear.

Phase errors can also be introduced into the forcing function due to varying distances between the sound sources and blades. The resulting phase error in degrees, θe, equals the distance error *e* divided by the wavelength of sound λ:

$$\theta e=360(e/\lambda) \qquad (1)$$

Because the wavelength λ can be written as the wave speed divided by its frequency, Eq. (1) becomes:

$$\theta e=360(e\,f/A) \qquad (2)$$

Both nonuniformity as wel as position errors were addressed by performing a calibration on the exciters to iteratively calibrate the forcing applied to each blade of a blisk so that differences among the blade forcing magnitudes can be minimized for single blade excitation. Also, the calibration ensures that the phases of the excitations applied to each of the blades can be accurately set for TWE.

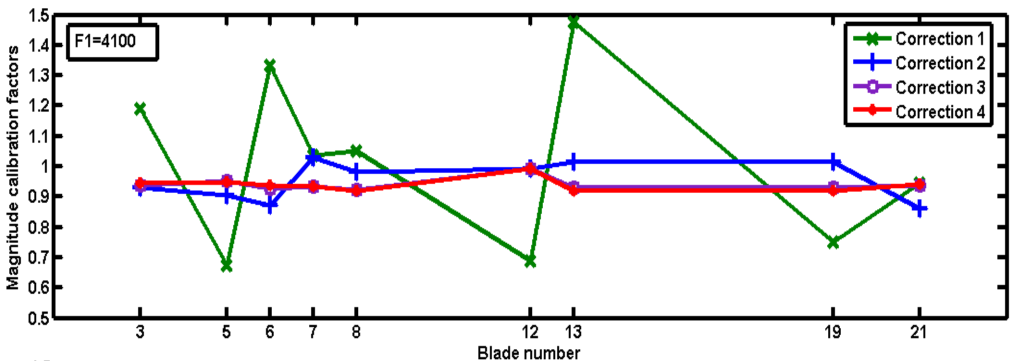
The calibration algorithm uses the principle of reciprocity and involves solving a least-squares problem to reduce the effects of measurement noise and uncertainty.

Experimental validation of the TWE calibration method on an industrial blisk was completed and is shown in Fig. 4. In the calibration process, because the blisk present a very complex geometry, where multiple blades are not coupled togheter at certain resonant frequencies, only a few blades were possible to be calibrated for the purpose of the new traveling wave excitation technique demonstration.

As can be saw from Fig. 4 testing the calibration procedure produced excellent results within a few iterations on the choosen blades and resonant frequencies. The magnitudes of the calibration factors at all their resonant frequencies have maximum and average values of 1.5 and 1.2, respectively. At the end of maximum four iterations, the maximum value is 1.01 and the average value is 0.99.

The phase corrections, present very good result from the beginning within an error of 0.5 degrees, for the choosen blades and resonant frequencies, fact that cancel out the necessity of applying the calibration procedures also in phase.

The calibration works for magnitude and phase, the results indicate how much actuation and accuracy the excitation system can produce. The first calibration can be performed using an engine-order-excitation 0 for which all blades are in phase. This provides a baseline for further testing and calibration.



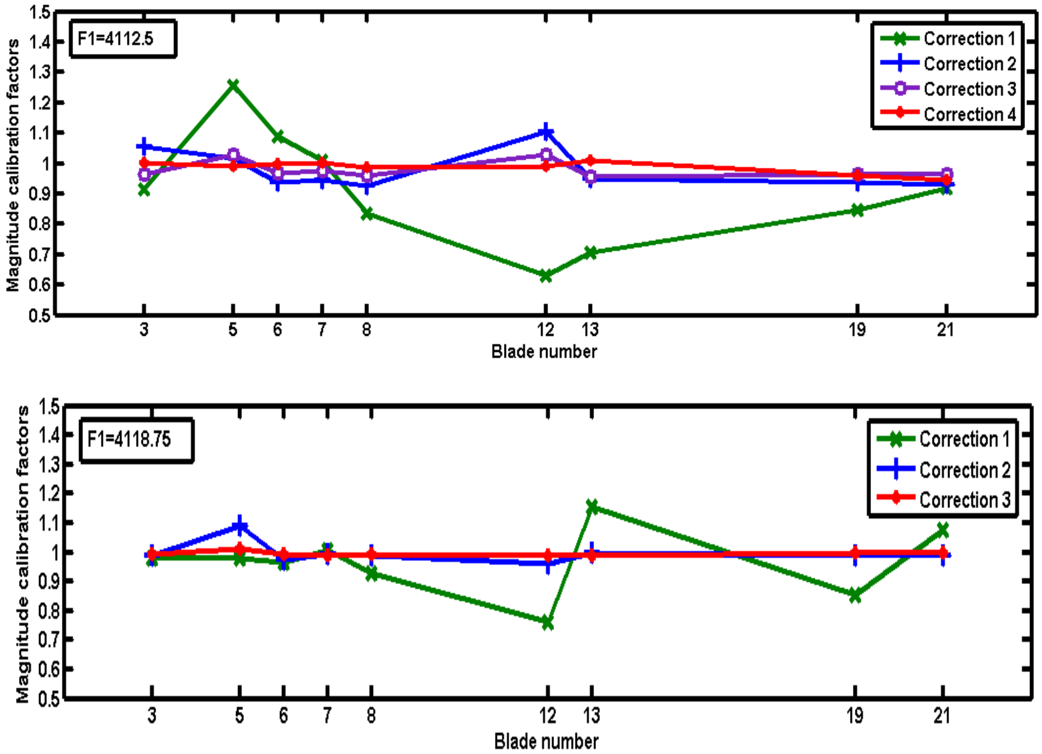


Fig. 4. Experimental results from four iterations of the calibration procedure for an engine-order-excitation 0, at three resonant frequencies of the first torsion fammily mode, for nine blades of a 23 industrial bladed disk

5. EXPERIMENTAL RESULTS

The 23-bladed disk shown in Fig. 5 was used to demonstrate the novell traveling wave excitation techinque. The structure considered is the first stage of a three-drum helicopter turbine rotor. The geometry of the blisk has the features shown in Table 1 and is made out of Ti alloy.

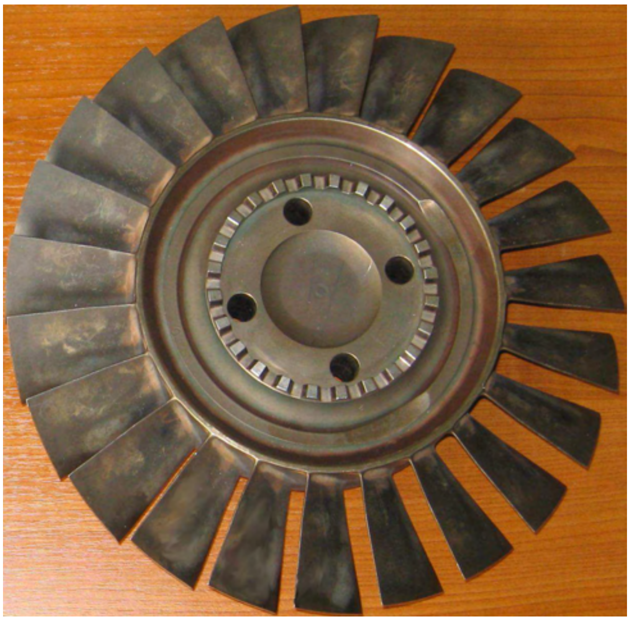


Fig. 5. The 23-industrial bladed disk used in the experimental testing

Table 1. Geometrical data of the 23-industrial bladed disk

disk radius	150 mm
blade height	55 mm
blade width in root section	35 mm
blade thickness at leading edge in root section	4 mm
blade thickness at trailing edge in root section	2 mm
blade thickness at leading edge in tip section	2.5 mm
blade thickness at trailing edge in tip section	1 mm
twist angle	30 degrees

The equation of motion for a blisk can be written as:

$$M\ddot{x}+(1+j\gamma)Kx=f(t) \qquad (3)$$

where γ is the structural damping, and M and K are symmetric mass and stiffness matrices. Considering harmonic motion, $x = Xe^{i\omega t}$ and $f(t) = Fe^{i\omega t}$. The matrix X can be written as:

¶ (10pt)

$$X=\begin{bmatrix} X_{11}e^{i\theta_{11}} & X_{12}e^{i\theta_{12}} & \cdots & X_{1n}e^{i\theta_{1n}} \\ X_{21}e^{i\theta_{21}} & X_{22}e^{i\theta_{22}} & \cdots & X_{2n}e^{i\theta_{2n}} \\ \vdots & \vdots & \ddots & \vdots \\ X_{n1}e^{i\theta_{n1}} & X_{n2}e^{i\theta_{n2}} & \cdots & X_{nn}e^{i\theta_{nn}} \end{bmatrix} \qquad (4)$$

The matrix X contains complex response amplitudes and can be written as the response amplitudes that have associated magnitudes X_{lk} and phases θ_{lk} where k and l vary from 1 to n. These response amplitudes correspond to excitation forces of magnitudes F_k and phases Ω_k. Indices *l* and *k* are the measured and excited blade numbers, respectively. Engine order excitation can be simulated in a stationary bladed disk by applying harmonic excitation to all blades where the excitation differs from blade to blade by a constant interblade phase angle Ω_k:

$$F_k = A\sin(\omega t + i\Omega_k) \quad (5)$$

$$\Omega_k = 2\pi\frac{C}{N} \quad (6)$$

where F_k is the forcing function on each blade and *C* is the engine order excitation. This type of excitation in a stationary bladed disk is referred to as traveling wave excitation.

The first torsion family mode was investigated. The bladed disk was excited using an analog sine wave engine order 1 excitation, $C = 1$. Because of the complexity of the bladed disk to be tested, only the nine blades that are active with considerable magnitude of vibration at the resonant frequency of 4100Hz and that were previously calibrated will be considered in the experiment.

The novell method consist in a computed TWE response of vibration of each of the blades starting from the response of single blade excitation in witch all blades were already calibrated and their responses are in phase. Adding to the single blade excitation response the correct interblade phase angle corresponding to the desired engine order excitation C, the computed TWE vibratory responses are obtained with an experimental accuracy presented below.

Through the rotary table the blisk is rotated such that the laser vibrometer is positioned on the tip of each of the 23 blades during testing. The data acquisition system was triggered to capture the function generator output and the blade response over exactly one cycle of the sine wave. The complex value frequency-response was then processed from the captured time signals. Ten averages were taken to reduce any noise in the data.

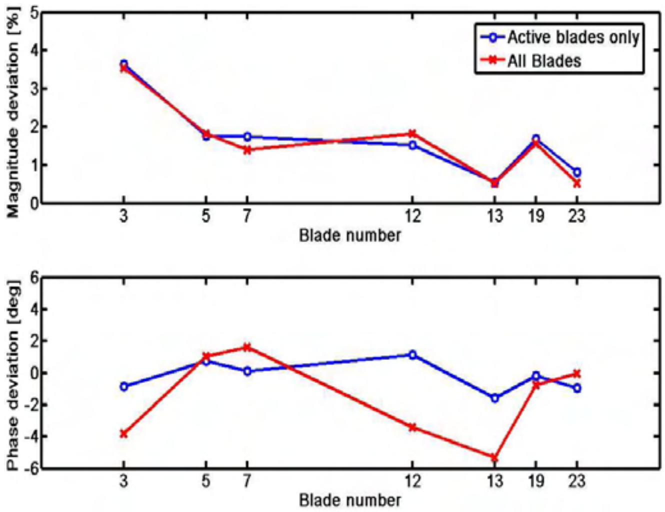


Fig. 6. Experimental results from two different cases of the novell TWE procedure for an engine-order-excitation 1 at the resonant frequency of 4100Hz of the first torsion family mode, for nine blades of a 23 industrial bladed disk

Figure 6 shows the difference in magnitude and phase deviations predicted by applying the exact travelling wave excitation of engine order 1 and measure the frequency response of the system and the method in which the TWE response was computed from a single excitation blade response of engine order 0. The magnitude deviation is defined as $\frac{X_{lk}^{TWE} - X_{lk}^{TWE_C}}{X_{lk}^{TWE_C}}$, where $X_{lk}^{TWE_C}$ are the TWE magnitudes of each blade frequency responses computed using single blade excitation response, and X_{lk}^{TWE} are the measured magnitudes of each blade frequency responses due to an acctually application of a travelling wave excitation of engine order 1 to the system.

The phase deviation is defined as θ_{lk}^{TWE} - $\theta_{lk}^{TWE_C}$ in degrees, where $\theta_{lk}^{TWE_C}$ are the TWE phases of each blade frequency responses computed from the single blade excitation phase response, and θ_{lk}^{TWE} are the measured phases of each blade frequency responses due to an acctually application of a travelling wave excitation of engine order 1 to the system.

As can be observed from Fig. 6 the computed TWE response predicts the blade magnitudes with less than 4% error compared to the actually TWE response. First, the novell technique was tested only for the nine active blades that respond at the resonant frequency of 4100Hz. The responses of all this nine blades were calibrated for engine-order-excitation 0 for which all blades are in phase as presented in the previous section. For this case the phase deviation between the computed and actually TWE response is about ± 1 degrees. In addition, all the other blades were supplied with excitation with independent phase difference, but were still measured for method validation purpose only the nine active blades. As can be observed from Fig. 6 the magnitude deviation for this case remains in the same margins of variation but the phase deviation increases with a variation in the interval from -6 to 2 degrees. The new method results are sensitive to the phase errors introduced by the phase responses given by the other blades that were excited, but the overall results are still good enough to validate the method. All this errors are due to experimental limitation and do not regard the incapacities of the method. The same technique was tested also computationaly using Ansys vibration results of the finite element model of the same bladed disk and Matlab tools and the responses predicted by the two techniques matches 100%. Note that the computational results are beyond the scope of this paper.

6. CONCLUSIONS

In this work, an integrated testing and calibration procedure was presented for performing traveling wave excitation (TWE) of bladed disks. The procedure yields accurate results and is highly efficient. First, a method was derived to iteratively calibrate the forcing applied to each blade of a blisk so that differences among the blade forcing magnitudes can be minimized for single blade excitation. Also, the calibration ensures that the phases of the excitations applied to each of the blades can be accurately set for traveling wave excitation (TWE). Experimental validation for the TWE calibration at engine order 0 on a blisk with complex geometry were presented. Second, a novell measuring travelling wave excitation technique was presented. In this method the TWE response at engine order 1 was computed from a single excitation blade response of engine order 0. Using the proposed method, the instrumentation cost and limitation are reduced to only one signal generation and a multiplexer circuit to comute the signal consecutively from one blade (exciter) to the other in order to perform single blade excitation. With this method, the need of generating simultaneously, as much analog sinewave as the number of blades in the tested bladed disk, with a high precision and accuracy in phase and magnitude, is cancel out. Therefore, the instrumentation cost and implication are reduced to minimum without tradding off the overall accuracy of performing travelling wave excitation in bladed disk structures.

7. ACKNOWLEDGEMENT
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8. NOMENCLATURE
Blisk(s) = bladed disk(s)

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