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Application Note

Acoustic Excitation of Turbomachinery Blisks

- Generating an engine order excitation
- Analyzing the dynamic responses of turbomachinery blisks
- Four sine excitation modes
- m+p's acoustic blisk excitation software
- m+p Analyzer for data capture and post-processing
- m+p VibRunner acquisition hardware

During operation wind, gas and steam turbine blades are subject to high dynamic forces introduced by the working fluid. In order to assess the structural health of the blades, dynamic analyses are carried out in laboratory tests. Highly specialized test rigs are designed for analyses of blades in rotating and stationary operating conditions. Especially for stationary tests, it is crucial to artificially replicate the typical excitations acting on the rotor blades during operation, known as engine order excitation. m+p international designed a software package which enables engineers to generate an engine order excitation and analyze the dynamic responses of the turbomachinery blisks in the safety of the laboratory.

Background:

During operation the working fluid acts on the rotating turbine blades, creating a pulsating pressure field. Circumferentially expanding this pressure field yields a harmonic series whose coefficients are called engine orders. Basically, an engine order describes the number of sine waves traveling along the circumference of the rotor (figure 1). The corresponding excitation frequency is the product of the rotational speed and the specific engine order, EO.

$$f_\mathrm{e} = \mathrm{EOf}_\mathrm{rot}, \quad \mathrm{EO} = 0, 1, 2, \ldots$$

Only a few engine orders will be encountered during operation. Thus, it is often possible to reduce the whole pressure field to a single engine order. m+p international's acoustic blisk excitation software replicates this engine order excitation by controlling the given actuators accordingly. Magnetic, acoustic, or electro-dynamic actuators are just some examples of the excitation sources that can be chosen according to the application needs based on the required excitation forces, excitation frequency range, etc.

Figure 1: Simplified bladed disks (blue) with pressure fields (grey) representing three engine order excitations:

Figure 1a: Engine order 1

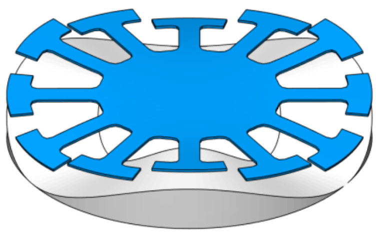

Figure 1b: Engine order 3

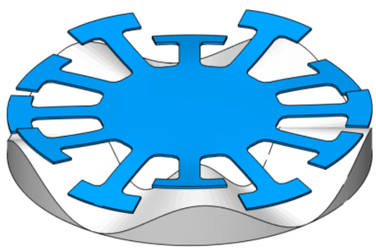

Figure 1c: Engine order 5

Figure 2a shows a common experimental setup in which one actuator is placed beneath each blade. Thus, the continuous circumferential pressure field (engine order) is replicated at discrete points (the actuators). For example, in a setup with 10 actuators, an engine order EO=3 is generated by replaying a sine wave of a given frequency on each loudspeaker and introducing constant phase lag between neighboring loudspeakers of:

$$\triangle\varphi = 360^\circ \cdot \mathrm{EO}/N_\mathrm{blades} = 360^\circ \cdot 3/10 = 108^\circ$$

Figure 2b demonstrates how this excitation replicates a steady-state operation of the machine at constant rotational speed. Run-up or run-down can be simulated by sweeping the excitation signal while keeping the required constant phase lag between the loudspeakers.

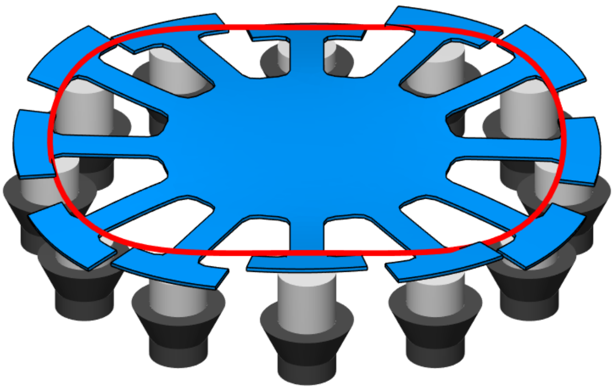

Figure 2a: Stationary blisk (blue) equipped with 12 speakers (black), sound pressure (grey) of each speaker adjusted to fit an engine order excitation

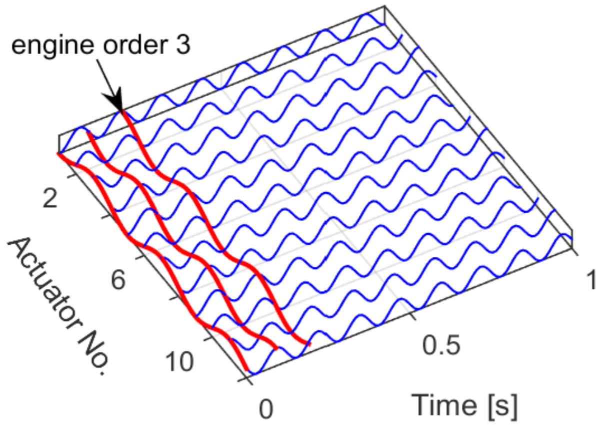

Figure 2b: Harmonic excitation signal (blue) for each speaker with relative phase lags adjusted to create an engine order 3 excitation (red)

This application note describes an acoustic excitation using loudspeakers, which is well suited for excitation frequencies above 1000 Hz. The experimental setup was developed together with the Institute of Dynamics and Vibration Research (IDS) at Leibniz Universität Hannover, Germany, and is used in several scientific research projects.

Experimental setup:

The experimental setup designed at IDS consists of a simplified bladed disk with 10 blades. In the center, the blisk is clamped on a vibration isolation table. Loudspeakers (type BMS 4540) are mounted on a rigid plate and placed beneath each blade. Acoustic amplifiers (type IMG Stageline STA 1508) are used to drive the loudspeakers. The input signals (excitation) are generated using m+p VibRunner hardware. Multiple m+p VibRunner chassis may be combined into a single multi-channel system, providing high output and input channel counts. Simultaneous sampling of all output channels ensures minimal phase error and high excitation signal quality, which is crucial in this type of application. The vibration response of the blisk is measured with accelerometers or a laser vibrometer.

Figure 3a: Experimental setup consisting of 10 rigidly clamped loudspeakers and a simplified blisk

Figure 3b: m+p VibRunner system used for input and output signals

Although the geometry of the IDS experimental blisk is very simple, it exhibits the main features of real world blisks such as traveling waveforms with different nodal diameters and mistuning effects. The m+p software provides a way to excite these traveling waveforms and measure the operational deflection shapes.

Typical test procedure:

Setting up the excitation system is a two-step process. The first step is to calibrate the system and the second step is to parameterize and configure the excitation. In order to calibrate the excitation system, the software offers a calibration routine (see figure 4a). All amplifiers and loudspeakers can be calibrated at distinct frequencies and amplitude levels. The results are saved to a database for future use and validation purposes. The configuration of the system is quick and straight forward (see figure 4b). The user only inputs the channel count, test frequency, engine order (nodal diameter) and amplitude level. Everything else is automatically generated by the m+p software. The excitation is available in four different modes:

- **Sine:** This is the most basic excitation type. The user selects a frequency, amplitude and nodal diameter, the software calculates the correct phase lag and generates the engine order excitation.
- **Custom Sine:** In this mode, the user can introduce arbitrary phase lags between output channels at given frequency and amplitude levels. This can be useful if the number of loudspeakers is not equal to the number of blades.
- **Periodic Chirp:** Performs a periodic chirp using the engine order excitation. This replicates the run up/down of a rotating machine.
- **Custom Periodic Chirp:** Like “Custom Sine”, the user can introduce arbitrary phase lags in this mode.

Standing wave excitation is also supported for all excitation types.

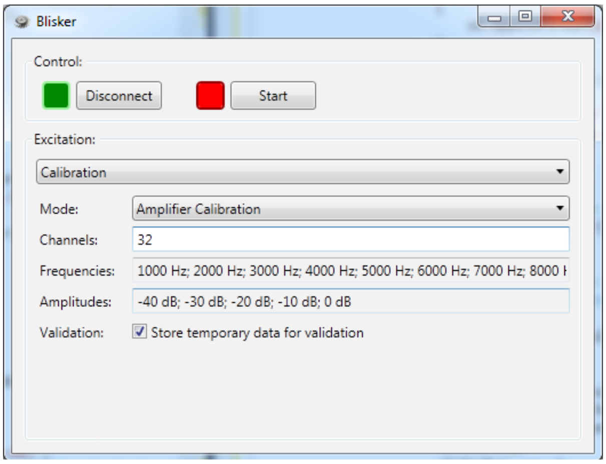

Figure 4a: GUI for amplifier calibration

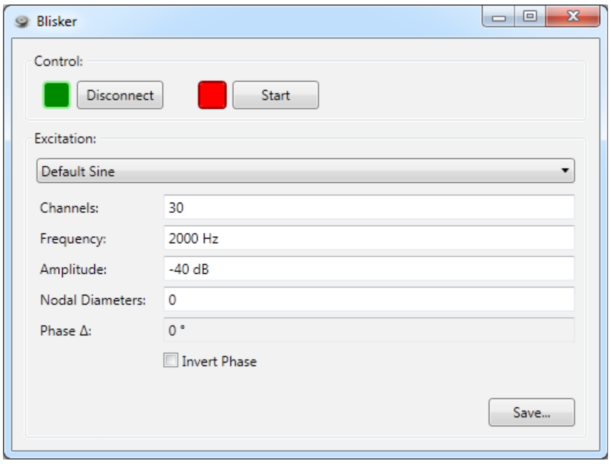

Figure 4b: GUI for sine excitation

Test results:

Typical test results are depicted in figure 5. A laser vibrometer was used to measure the tip amplitude of each blade in the frequency range from 1180 Hz to 1220 Hz. All data was acquired using m+p Analyzer, a multi-purpose measurement software capable of acquiring and post-processing huge amounts of data. m+p's acoustic blisk excitation software was configured to harmonically excite the engine order three (EO=3). The loudspeakers produced a rotating pressure-field with three circumferential waves. As can be seen in figure 5a, the response of the individual blades is harmonic but phase-shifted. Just like the phase lag of the excitation between two adjacent loudspeakers was 108° (EO=3), the phase lag between the responses of two adjacent blades was also 108° (see figure 5b). Note that the maximum amplitude of all blades is nearly identical because of the rotating nature of the mode shape. Small differences in amplitudes of the individual blades are expected due to mistuning effects resulting from material and manufacturing imperfections.

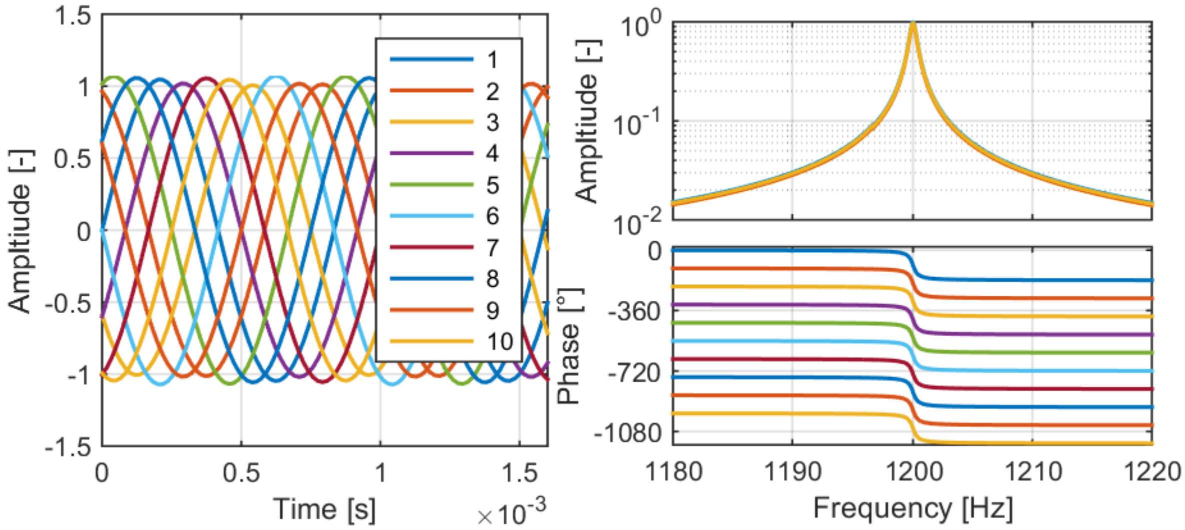

Figure 5: Left: Measured time history at each blade tip under excitation with engine order 3 at 1200 Hz
Right: Phase-referenced spectra of the blade responses in the frequency range from 1180 to 1220 Hz (phase ref. at 1180 Hz blade 1)

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