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Transient vibration characteristics of a rotating multi-packet blade system excited by multiple nozzle forces

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ABSTRACT

For the design of a rotating multi-packet blade system excited by multiple nozzle forces, transient and steady-state vibration characteristics of the system need to be identified accurately. The present study derives equations of motion of a rotating multi-packet blade system excited by multiple nozzle forces using the Rayleigh–Ritz assumed mode method. Using the equation model, resonance frequencies and their strengths are first identified. The study then investigates the effects of system parameters such as number of nozzles, number of packets, shroud coupling stiffness, disk coupling stiffness, damping constant and spin-up time constant on the transient response during a spin-up or spin-down motion which makes the nozzle passing excitation frequency pass through multiple resonance frequencies as well as the steady-state response around an operating angular speed.

1. Introduction

A turbine generator is a typical example that includes a rotating multi-packet blade system excited by multiple nozzle forces. Several blades connected through a shroud are grouped as a packet, and multiple packets constitute a multi-packet blade system. Shrouds as well as a disk to which all blades are attached generate stiffness coupling between adjacent blades. Vibration characteristics of rotating multi-packet blade systems are influenced by system parameters such as number of nozzles, number of packets, shroud coupling stiffness, disk coupling stiffness, damping constant and spin-up time constant. Therefore, the effects of such parameters on the transient and steady-state vibration characteristics of the multi-packet blade system need to be identified accurately for the system design.

A study on the modal characteristics of a rotating structure was pioneered by Southwell and Gough [1]. An analytical model called the Southwell equation was introduced to calculate the natural frequencies of a single rotating blade based on the Rayleigh energy theorem. Following this study, a large amount of literature related to rotating blades has been published. See some literature survey papers [2,3] for more information on the subject. Various elastic, inertia, and geometric effects such as shear, warping, rotary inertia, eccentricity, concentrated mass, pre-twist, cross-sectional variation and installation angles were considered to investigate the modal characteristics of a single blade. However, a relatively small number of papers [4–7] related to multiple blade systems can be found in the existing literature.

Even for a single blade, deriving governing equations for the vibration analysis is burdensome [8]. Using a conventional modeling method, nonlinear equations of motion should be obtained first and should then be linearized around a dynamic equilibrium position to obtain the final equations for the linear vibration analysis. Since the burden multiplies as the number of blades increases, deriving the equations of a multi-blade system using the conventional modeling method is improper. To overcome the drawback of the conventional method, an enhanced modeling method was introduced [9,10]. While the conventional modeling method employed only Cartesian deformation variables, the enhanced modeling method employed hybrid deformation variables. Thus, it is often called the hybrid deformation variable modeling method. Linear governing equations could be derived directly using the modeling method. Coriolis coupling effects between stretching and bending motions of a blade could also be incorporated [11] into the equations of the model. This modeling method was also employed for the modal analysis of a rotating multi-packet blade system [12]. The accuracy of the modal analysis results was validated.

One of the most important considerations in the design of a rotating multi-packet blade system is to identify the resonance frequencies. If a natural frequency of the system coincides with a frequency component of the excitation force, then dynamic

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responses of blades may become sufficiently large to cause structural failure. To prevent the system from operating around a resonance condition, resonance frequencies should be identified. Campbell diagrams are frequently used to determine resonance frequencies. However, many frequencies may be mistaken for resonance frequencies with a Campbell diagram. To overcome the drawback of the Campbell diagram, a different diagram was proposed [13–15]. This diagram (often called the SAFE diagram) includes the additional dimension of mode information. By including the mode information, true resonance frequencies could be identified.

For the design of a rotating multi-packet blade system excited by multiple nozzle forces; however, forced vibration characteristics should be accurately estimated since strength design should be carried out based on forced vibration responses. Typical forced vibration responses requested for the strength design include steady-state responses of the system around an operating frequency and transient responses of the system during a spin-up or spin-down motion that passes through resonance frequencies. There existed some research activities related to forced vibration responses of bladed disk assemblies. Reference [16] provides a detailed review of a number of papers related to forced vibration responses of bladed disk assemblies. More recently, effective methods [17–19] to obtain forced vibration responses for bladed disk assemblies were proposed. In these papers, however, the effects of system parameters on the forced vibration responses of a multi-packet blade system were not investigated. Incidentally, the transient response characteristics of a multi-packet blade system during a spin-up or spin-down motion that makes the excitation frequency pass through resonance frequencies have never been investigated in the previous works.

The purpose of the present study is to propose an accurate and efficient forced vibration analysis model of a rotating multi-packet blade system excited by multiple nozzle forces. The reliability of the model is first examined by obtaining transient responses at true and pseudo-resonance frequencies. Resonance strengths are also examined with the proposed model. The present study primarily investigates the effects of system parameters such as number of nozzles, number of packets, shroud coupling stiffness, disk coupling stiffness, damping constant and spin-up time on the transient response of the system during a spin-up or spin-down motion which makes the excitation frequency passes through resonance frequencies.

The main novelty of the present paper lies on the modeling and the analysis results obtained using the proposed model. Since the transient characteristics of a rotating multi-packet blade system during a spin-up or spin-down motion which makes the excitation frequency pass through resonance frequencies cannot be obtained properly with steady-state responses, a transient analysis model is introduced to obtain the results. Such a transient analysis model has never been introduced in previous works. Also the effects of several parameters on the transient as well as steady-state characteristics of the system are investigated. These results were never obtained in previous works.

2. Modeling for the transient vibration analysis

The principal objectives of the present study are to propose a forced vibration analysis model of a rotating multi-packet blade system excited by multiple nozzle forces and to investigate the effects of system parameters on the transient and steady-state vibration characteristics of the system. The following assumptions are made to focus on the principal objectives of the present study while avoiding unnecessary formulation complexities. All blades are idealized as homogeneous isotropic slender straight beams fixed vertically to a rigid disk. Only in-plane bending motion of the beam is considered for the simplicity of formulation. Disk and shroud flexibilities are idealized as discrete springs. The angular motion of the disk is prescribed as a function of time. With the above assumptions, the equations of motion of a rotating multi-packet blade system excited by multiple nozzle forces are derived using the Rayleigh–Ritz assumed mode method.

Fig. 1 shows the configuration of a typical multi-packet blade system excited by multiple nozzle forces. Multiple blades connected through a shroud constitute a packet, and multiple packets constitute the system. Multiple nozzle forces that are separated equidistantly act on the blades serially as the disk rotates. Fig. 2 shows the idealized multi-packet blade system, in which all blades are modeled as slender straight beams, nozzle forces are modeled as force vectors and the flexibilities of the disk and shrouds are

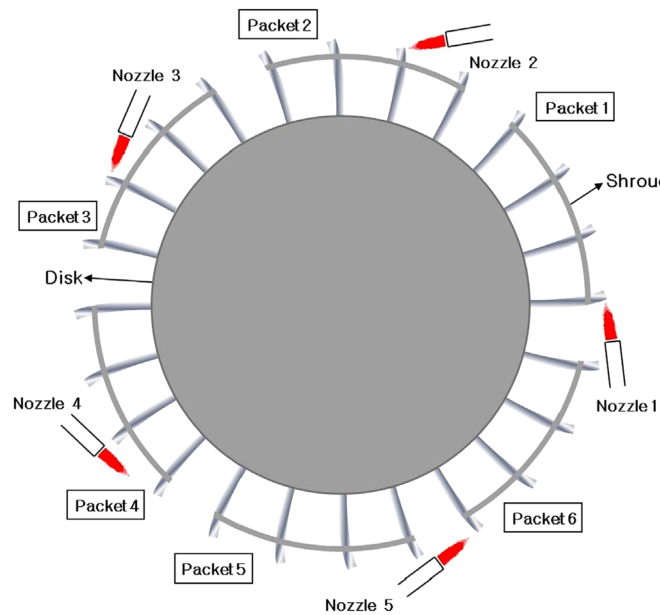

Fig. 1. Multi-packet blade system excited by multiple nozzle forces.

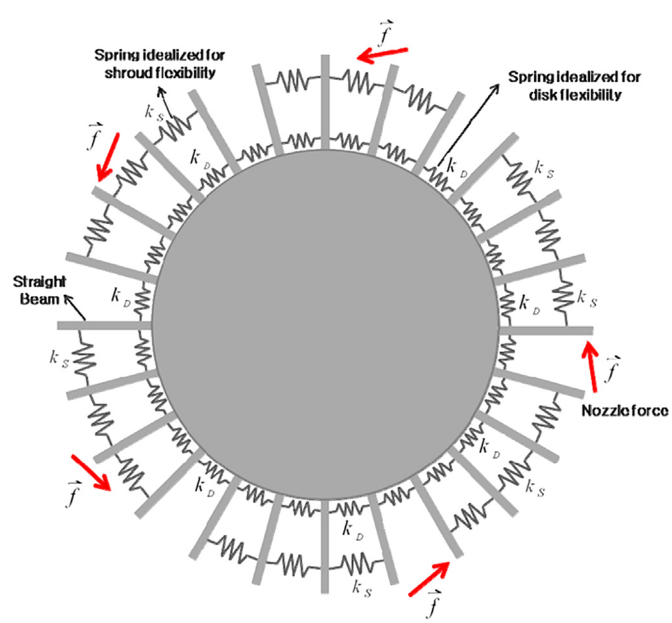

Fig. 2. Idealized model of the multi-packet blade system.