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Measurement versus predictions of rotordynamic coefficients of seal with swirl brakes

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ABSTRACT

Seal rotordynamic coefficients have a primary influence on stability response of high-performance turbomachinery. The swirl brake is one approach to improve the rotordynamic characteristics of seals. Although swirl brakes have been used successfully in practice, the experimental studies dealing with the rotordynamic coefficients associated with different swirl brake geometries as well as operating conditions are very spare. The present research investigates the effects of the swirl brakes on the rotordynamics of labyrinth seals. Experiments are presented to identify the stiffness and damping force coefficients using an improved impedance method based on unbalanced synchronous excitation method on a rotating test rig. Several design parameters, such as swirl brake density and length have been considered and also the operating conditions (inlet/outlet pressure ratio and rotating speed) are accounted for. Test results demonstrate the pronounced favorable influence of the swirl brake to effectively reduce the cross-couple stiffness and increase the direct damping for variable conditions. It is believed that the results of this study will assist in improving the design of annular seals.

1. Introduction

Seals are widely used in compressors and turbines to restrict leakage flow through rotor-cylinder clearances from a high-pressure region to a low-pressure region. They have been confirmed as a major source of destabilizing forces resulting in rotordynamic instability problems [1–5]. Extensive experimental investigations and field troubleshooting experience have confirmed the cross-coupling stiffness generated by gas preswirl velocity at the labyrinth seal entrance to be the major mechanism of inducing a load-dependent instability vibration [6–8].

Gases following axially along the shaft may have a circumferential component referred to as a swirl. Labyrinth seals with strong gas swirl in the direction of rotation of the shaft can generate a destabilizing force that may induce rotor instability. This is primarily influenced by the swirl velocity at the entrance to the labyrinth seal. In practice, shunt injection and swirl brakes are standard tools to enhance rotor stability if the predicted log-decrement is relatively low [9,10].

Shunt injection has proven its positive influence in many machines that show stable operation, even though some cases are known in which they have not produced satisfactory effects [10–13]. The requirement that the rotor should have the largest possible stiffness (for which the shortest possible bearing span should be implemented) runs contrary to the idea of also employing shunt-holes on impeller eye seals and not just on the balance drum labyrinth. A further disadvantage is the loss of efficiency caused by shunt injection. A doubling

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of the leakage was ascertained during the investigations made by Azuaje [14] on labyrinths with shunt injection installed. It may therefore be useful to look for other effective measures for inlet swirl reductions that do not exhibit the disadvantages mentioned above.

An alternative solution is to be found in the use of swirl brakes. When adopted with balance pistons or center seals, the swirl brakes are typically installed behind the impeller and outside the labyrinth seal. Swirl brakes are a series of vanes provided at the seal entrance to impede or direct the entrance flow of circumferentially rotating fluid to improve high-performance compressor stability. Benckert and Wachter [15] presented the first test results demonstrating their effectiveness, the test results showed that lowering the preswirl via swirl brakes could reduce the destabilizing rotordynamic forces. Gans [16] suggested that the stability of a steam turbine could be improved by employing anti-swirl vanes. The vanes are intended to induce fluid rotation against shaft rotation and thus reduce the destabilizing effects of a combined labyrinth-brush seal. Nielsen and co-workers [17,18] were the first to study, by means of CFD, the application of swirl brakes in the region feeding the wear ring seal of a pump impeller. Moore and Hill [19] presented an optimization study of the swirl brakes applied to impeller eye seal of a high-pressure centrifugal compressor using CFD techniques. More recently, Nielsen [20] compared two interchangeable swirl brake designs, which are considered to be effective in terms of reducing the seal inlet swirl and thereby improving rotordynamic stability. Although swirl brakes are widely implemented, experimental studies dealing with the rotordynamic coefficients associated with different swirl brake geometries as well as operating conditions are very spare.

In this paper, the effectiveness of the swirl brakes was experimentally investigated when used with the labyrinth seals on a rotating test rig. An improved impedance method based on unbalanced synchronous excitation method was used to investigate the rotordynamic coefficients of seals. Several design parameters, such as swirl brake density and length have been considered, and the operating conditions (pressure level and swirl at the swirl brake inlet) were also accounted for.

2. Test-rig description

Fig. 1 depicts our rotordynamic test rig. A slender steel shaft is supported by two steel oil journal bearings lubricated by ISO VG32 turbine oil. The middle of the shaft holds a steel sleeve coupled with labyrinth seals and with a diameter of 180 mm. Near the bearings, two steel balance disks are used to regulate the original vibration of the rotor and provide unbalanced exciting forces. The magnitudes and angles of unbalanced excitation forces can be changed through changing the location of unbalance blocks, which are fixed on the balance disks. Six rings of copper labyrinth seals are fixed on the interior wall of the cylinder. The cylinder is hung by springs (which can be exchanged to adjust stiffness) from vertical and horizontal directions. The cylinder is ensured to be easily excited only by seal force which has approximately the same frequency as the rotor rotation. At the shaft's free end, a 15 KW dc motor drives the shaft through a 4.5:1 ratio speed-increasing gearbox via a disc-type coupling. The rotor speed can be adjusted from 500 rpm to 6000 rpm. In order to obtain the impedance function of the cylinder, an electromagnetic shaker is used for applying dynamic load to the cylinder with loads up to 500 N. The dynamic load applied to the cylinder is measured with the load cell located between the stinger and shaker frame. In order to investigate positive preswirl test to explore the potential impact of swirl brakes, four air inlet pipes which feed in the middle of the cylindrical, are equally spaced on the circumference. Each inlet pipe lies at a 45 degree angle between tangential direction of the rotor surface and the direction of the inlet pipe. The inlet pipes therefore provide positive preswirl which indicates that the inlet gas is rotating in the same direction as the rotor.

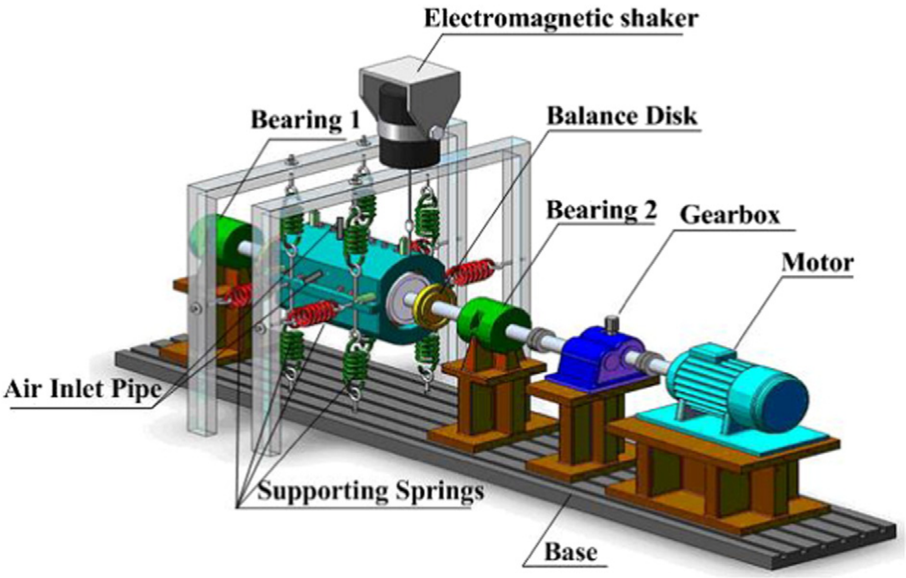

Fig. 1. Schematic diagram of the seal test rig.