INSTABILITY OF PUMP ROTORS WITH LOW-VISCOSITY WORKING MEDIA IN ZERO GRAVITY

Jiří ŠIMEK[1] & Michal VAJDÁK[2]

Abstract: *The paper offers an analysis of the rotor and bearing system for the ammonia pump concept design for space applications. It exemplifies distinct rotor self-excited instability types known as "oil whirl" and "oil whip" caused by fluid dynamic forces generated in the media-lubricated bearing. These instability types were observed experimentally and were analyzed from data obtained during various machines operation. The application of tilting pad journal bearings to ensure the stability of high-speed rotors with bearings working with extremely low-viscosity fluid and in zero-gravity conditions is investigated in the paper.*

1. Model and results

The rotor of the ammonia pump was supported in hydrodynamic bearings lubricated by the process fluid with a corresponding dynamic viscosity of 1.68×10^{-4} Pa.s (2.62 MPa, 275 K). Journal bearings working with low viscosity fluids are prone to instability, especially in zero gravity conditions.

We designed the pump with tilting pad journal bearings (TPJB) 6 mm in diameter. To compare the behavior of the pump with TPJB and with cylindrical bearings with four axial grooves used in [1], we carried out a dynamic analysis of both variants. The cylindrical bearings had the equivalent relative clearance of 2.6×10^{-3}.

The rotor model (Fig. 1) with a mass of 0.05 kg and bearing span of 68 mm indicated **rotor instability starting at 11 000 rpm** in cylindrical four-groove bearings, while with TPJB the rotor was stable in the whole speed range up to 30 000 rpm.

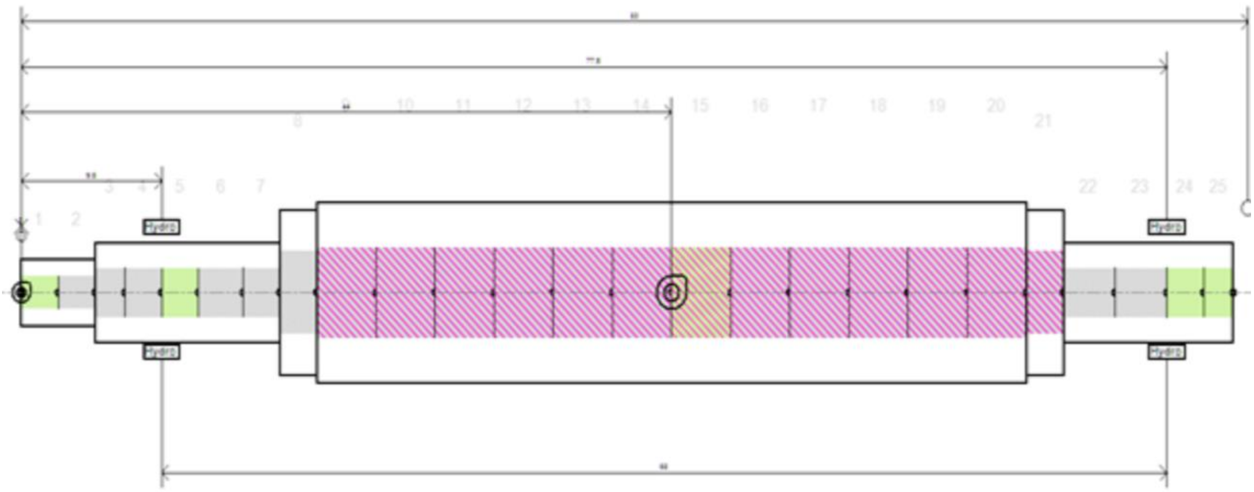

Fig. 1 Model of the substitute rotor

Such ammonia pump rotors can exhibit instability, especially in zero-gravity conditions, with no static load acting on the bearing. That is why instability cannot be discovered during tests in an earthbound laboratory.

2. Instability types

Rotor instability is a notably dangerous phenomenon with amplitudes of vibration attaining the whole bearing clearance and characterized by subharmonic frequency. With gas lubricated bearings rotor instability evokes **in most cases** an instant failure with heavy bearing damage. Bearings lubricated by liquids can be operated for a long time in regime of instability because bearing sliding surfaces are lubricated and cooled by the liquid. The immediate failure is also prevented by nonlinear bearing characteristics with the fluid film stiffness substantially increasing with decreasing thickness. Nevertheless, such a regime results in extensive wear of sliding surfaces, as was reported in [1]. Instability can be stopped only by reducing the speed below the stability limit, however in most cases, there is some hysteresis, i.e., instability disappears at a lower speed than that at which it occurred.

There are two basic types of rotor instability:

a) “Oil whirl“, with subharmonic frequency dependent on rotational speed, is more likely encountered with rigid rotors. It is caused by forces generated in bearings. Paradoxically this type of instability occurs mainly with rotors in gas bearings, which could not pass through bending critical speeds. Record of vibration amplitudes during the instability of rotor in gas bearings at the speed of 30 000 rpm are shown in Fig. 2. Top-down are signals of the speed control signal, relative vibration in the vertical direction at the turbine and compressor rotor end. It can be seen that the dominating vibration frequency is subharmonic, with a double amplitude of vibration exceeding 100 μm.

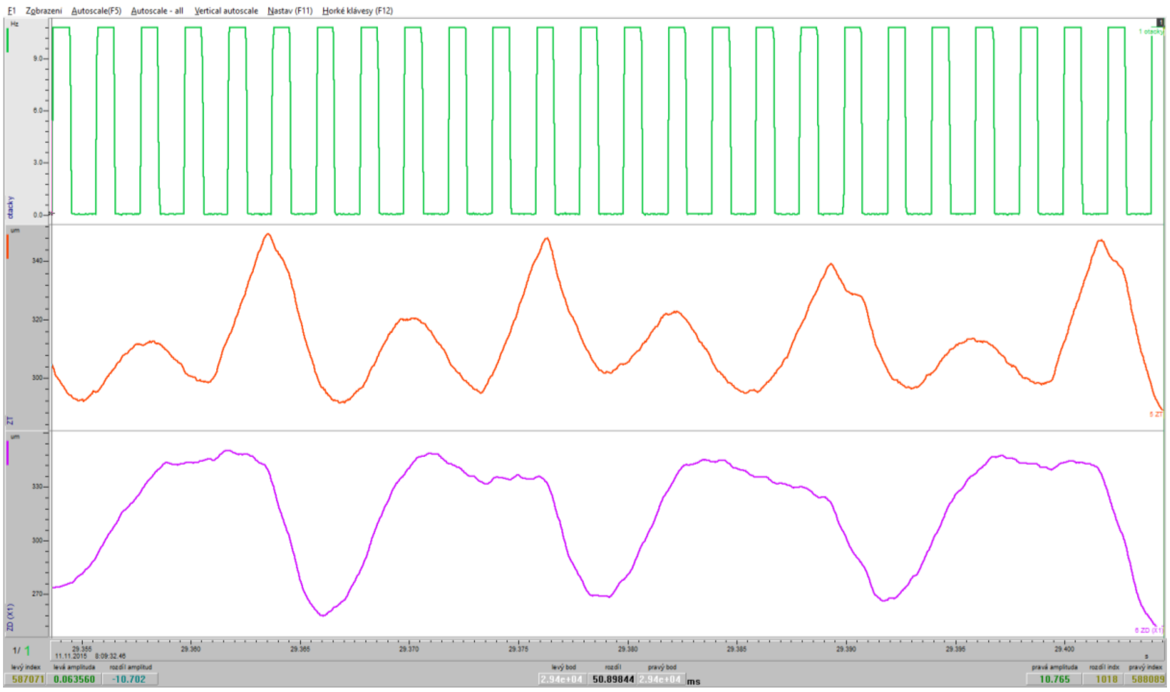

Fig. 2 Rotor instability of the “oil whirl” type

b) “Oil whip” type of instability, encountered in the operation of flexible rotors, which pass through at least one bending critical speed. It is characterized by a constant subharmonic frequency equal to the lowest natural frequency of the rotor system. Fig. 3 shows the instability of a steam turbine rotor at a speed of 5 500 rpm with maximum vibration amplitudes around 100 μm.

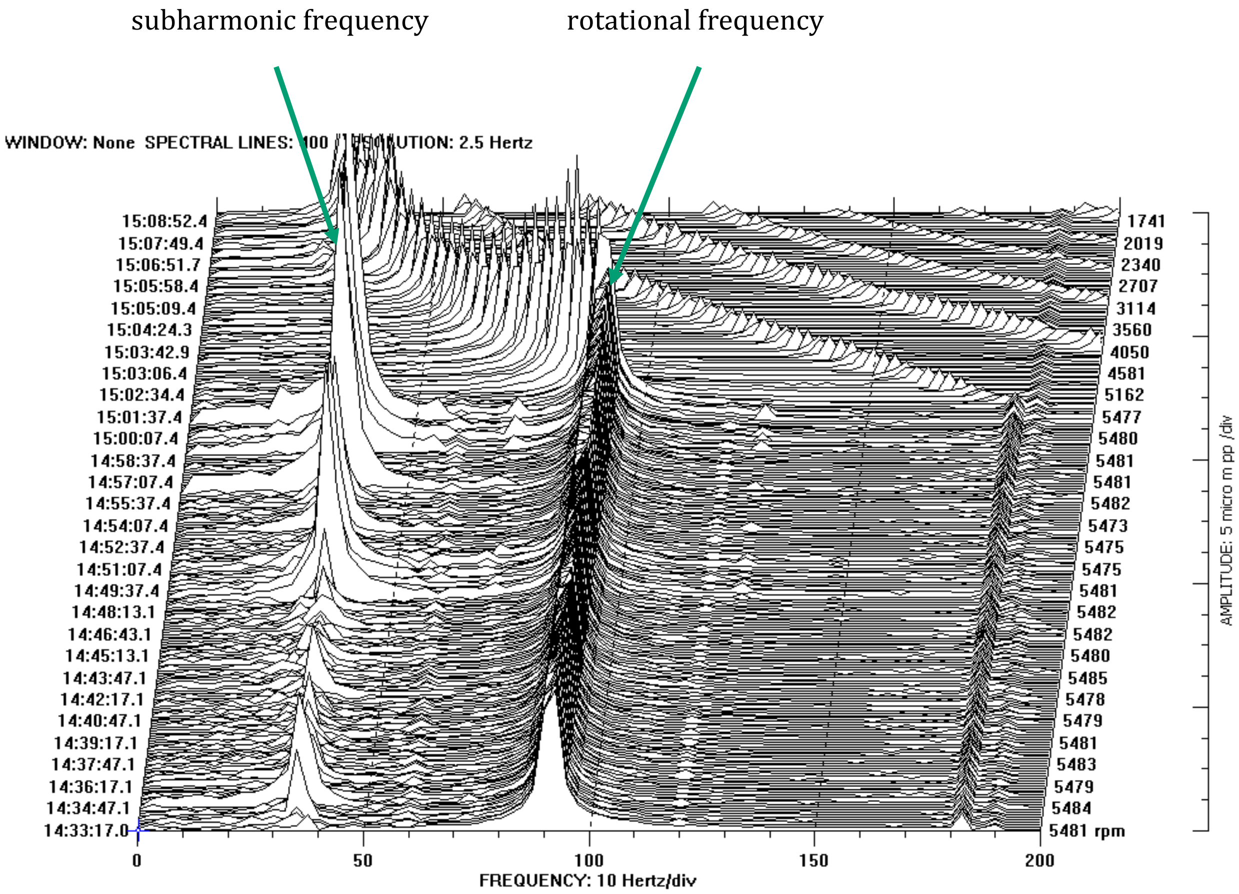

Fig. 3 Rotor instability of “oil whip” type

It is possible to see a very rapid increase of subharmonic frequency with increasing **turbine** power. When the machine was shut down by the diagnostic system, the vibration with subharmonic frequency disappeared.

While in case sub 1) the instability is influenced predominantly by the bearing geometry, in case sub 2) it is a combination of the bearing and rotor properties. In dynamic rotor analysis, the instability is indicated by the positive real part of the system eigenvalue, while the imaginary part of the eigenvalue determines vibration frequency. It is essential to reveal potential instability already in the phase of machine design because solving such a problem on already produced machines is very costly and time-consuming.

For high-speed rotors with bearings working in the environment of extremely low viscosity fluid, it is **essential** to use bearings, which can ensure stability even in zero-gravity conditions. In most cases, it is necessary to use tilting pad journal bearings (TPJB) characterized by very low cross-coupling stiffness terms [2]. Cross-coupling stiffness terms, which promote the orbital motion of the journal around the bearing center, thus causing instability, are in TPJB at least two orders lower than principal stiffness terms. For applications with standard viscosity fluids, it is possible to use TPJB with five or four pads (Fig. 4, 5). However, in fluids with extremely low viscosity, it may be necessary to apply a special three-pad design (Fig. 6) to generate sufficient hydrodynamic pressure.

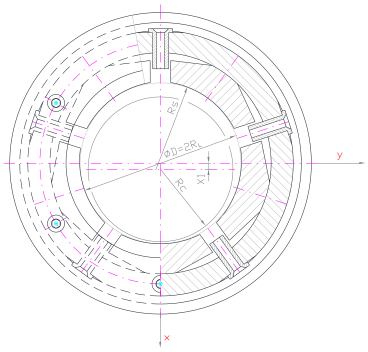

Fig. 4 Five-pad TPJB

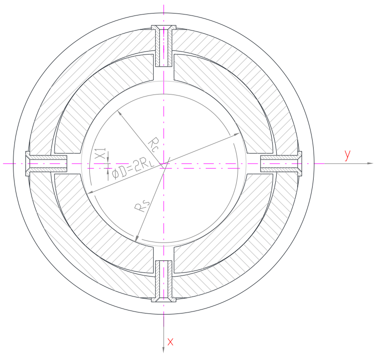

Fig. 5 Four-pad TPJB

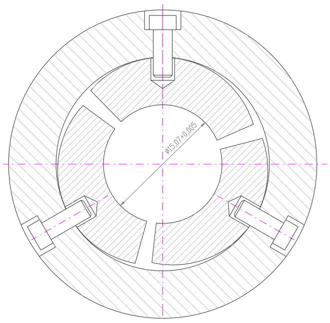

Fig. 6 Three-pad TPJB

It is evident that high-speed rotors lubricated with process fluid of extremely low viscosity and operating in zero-gravity had to be supported in a special type of TPJB. We have broad experience with the design and operation of this type of bearings both for fluid and gas process medium. That is why we used TPJB lubricated by low viscosity media with an operating speed of 30 000 rpm and even more.

References:

[1] Bruckner. R. J. – Manco, R. A.: ISS Ammonia Pump Recovery, and Lesson Learned – A Hydrodynamic Bearing Perspective. Proceedings of the 42nd Aerospace Mechanism Symposium, NASA Goddard Space Flight Center, 2014

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[1] **Ing. Jiří ŠIMEK, CSc.** is an esteemed bearer of the Czech engineering tradition in rotor dynamics and the design of rotary machines. He received his PhD. from the Pilsen University of Technology. He has published extensively in academic journals on the topics of machine bearings, machine control, testing, and vibration control. His long-term research and development efforts, whose origins date back to the 1970s and are associated with the Research Institute for Machine Design in Běchovice, were gradually developed by private companies in the Czech Republic since the early 1990s.

[2] **Ing. Michal VAJDÁK** is an engineering expert in rotating systems and subsystems development and an award-winning innovation manager advocating a holistic approach to leadership within tech companies and emphasizing the efficiency of synergic management of R&D engineering, planning, IT, production, and communication. His technological focus revolves around high-speed rotating machines, gas-lubricated bearings, and DIC optical measurement. In 2017, the effort to adapt high-speed rotary machine technology into a new low-volume product led to a joint project with the European Space Agency to develop a European unique electric cycle engine.