Asymptotic description of the wear process in dry-running reciprocating compressors

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Summary. The dynamics of sealing elements within a reciprocating compressor is considered in a 2D model as described in [1]. Linear elastic effects of the sealing ring, periodically changing gas pressure loads driven by the external piston movement and dry wear at the moving contact surface between the ring and the piston rod are explicitly included. Two governing equations for the dynamical quantities of interest are specified, together with three small, non-dimensional parameters characterizing the problem. Following [3], an asymptotic analysis is sketched, involving two time scales, where rapid changes due to the compression cycle as well as slow changes due to wear are considered.

Introduction

We consider the dynamics of sealing elements typically used in industrial reciprocating compressors or pumps. So called packing elements seal the higher gas pressure in the compression chamber against the lower ambient pressure. These elements consist of one or more packing rings held in so called cups within a packing housing. The ring seals the gas pressure dropping from P_1 on the cylinder side to P_2 on the crank side by being pressed against the facing side of the cup on the right and to the moving rod below, see Figure 1, taken from [1]. Depending on the sealing efficiency, there is an (undesired) gas flow from left to right.

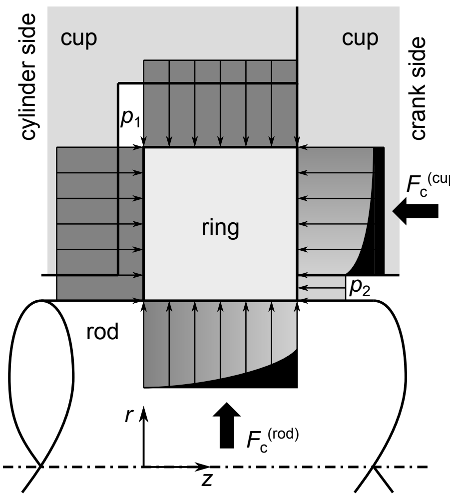

Figure 1: Gas pressure and contact forces acting on a sealing ring, taken from [1].

The rod is connected to a piston in the compression chamber and moves periodically in horizontal direction, driven externally by a motor running at a fixed frequency, creating a desired delivery pressure. This gives rise to a periodically changing pressure P_1 in the cup. Due to the dynamic contact between ring and rod, the process is subject to dry wear leading to material loss on the inner side of the ring.

Problem formulation and model

We completely adapt the analytical axisymmetric 2D model for the sealing ring from [1], see Figure 1. The ring material is described by Hooke's law and is assumed to be in a state of plane strain. Stresses and strains are functions of the radial coordinate r only. The contact force from the rod is uniformly distributed in (axial) z-direction, giving rise to a contact pressure P_c, and a ring wear that does not depend on z. In contrast to [1], we assume a periodically changing pressure P_1 on the upper side of the ring and a periodically moving rod on the lower side. Gas pressure effects over the contact surface, friction forces and inertial effects are ignored. Depending upon the contact pressure P_c, ring material is worn away over a large time compared to the compression period length. Archard's wear law is used to describe the wear process, where the long term wear rate and the course of the contact pressure P_c are the quantitites of interest.
Due to the wear process the inner radius $R^{(i)}$ of the ring grows, and so does the displacement $u^{(i)}$ in radial direction as to fulfill the contact condition $R^{(i)} + u^{(i)} = D/2$ with D being the rod diameter. Combined with Archard's law, a governing equation for $R^{(i)}$ as a function of time may be derived, where the gas pressure P_1 is acting as an external excitation.

Asymptotic description

Writing down the equations in non-dimensional form, one can identify two small, non-dimensional parameters governing the problem:

$$\varepsilon := \frac{KV_0 P_D}{(D/2)\omega}, \quad \delta := \frac{P_D}{E}. \tag{1}$$

K is the wear coefficient from Archard's law, V_0 is a reference velocity (amplitude) of the rod movement, the discharge pressure P_D is serving as a reference pressure, ω is the angular frequency of the piston movement, and E is Young's modulus of the ring material.According to [1], for practical cases the relationship $\varepsilon = \mathcal{O}(\delta)$ is valid, i.e. ε being much smaller than δ.
Asymptotic investigations of the problem were already performed in [3], where the parameter ε (though defined slightly different) was identified. In [3], a somewhat idealized physical situation was investigated and analyzed by the method of multiple scales.
Introducing the non-dimensional quantity $\rho := R^{(o)}/R^{(i)}$ being the quotient of the constant outer ring radius $R^{(o)}$ to the time-dependent inner ring radius $R^{(i)}$, the following governing equation may be derived:

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -\varepsilon \, \frac{\dot{p}_1 p_c \rho}{1 + \delta \, r_o \frac{\rho}{1-\rho^2}(p_c - p_1)}. \tag{2}$$

Here t is the dimensionless time, p_1 is the dimensionless gas pressure, p_c the dimensionless contact pressure, and r_o the dimensionless outer ring radius. The gas pressure in equation (2) may be considered as a given periodic excitation function with the (constant) frequency of the piston movement. Equation (2) is supplemented by a non-linear, algebraic equation resulting from the contact condition between ring and rod, involving the dynamical quantities ρ and p_c. Thereby, the quantity ρ is directly related to the wear rate.
The parameter δ expresses the relative size of the involved gas pressures compared to the material stiffness of the ring, being of the order of 10^{-2} in practical situations. The much smaller parameter ε characterizes the wear process taking place on a much slower timescale compared to the dynamics arising from the compression cycle. We address to tackle the problem by performing a coupled asymptotic expansion of the equations with respect to ε and δ, taking into account that $\varepsilon = \mathcal{O}(\delta)$. In in analogy to [3], we introduce two timescales t and εt to seek for a solution within a multiple scales analysis.

Summary and conclusions

We considered the dynamics of a sealing element within a reciprocating compressor, being subject to dry wear on the moving contact between sealing ring and piston rod. Based upon previous works [1]-[3], we have specified two governing equations for the dynamical quantities ρ (a dimensionless inverse inner ring radius) and the dimensionless contact pressure p_c. These quantities are affected by rapid changes due to the piston movement and slow changes due to the wear process. A small parameter ε distinguishes between the two time scales and may serve as an asymptotic parameter for a calculation of perturbations to solve the governing equations.

References

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