Tribological study of an aerodynamic thrust bearing in the supersonic regime

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Abstract. Nowadays, aerodynamic air thrust bearing are mainly used over a large panel of turbo-machineries. These systems become increasingly faster and up to operate in supersonic regime. They have not reached a sufficient level of research in terms of high speed. The possibility of an aerodynamic thrust bearing operating in a supersonic regime is studied. First, the air film dynamic study for high Reynolds number is based on the “modified Reynolds” equations, which take into account the inertia terms, the viscosity’s variation in the film thickness, and the turbulence. It’s an extension of the traditional model used in lubrication called the generalized Reynolds equation. The results show that a depression occur at the location of the change of slope of the tapper flat geometry. The hypothesis of presence of shock or rarefaction waves shows that the pressure gradient in the film thickness may be no longer negligible. The modified Reynolds equation may be not enough to describe the problem. A new system is built to study these phenomena: the Navier-Stokes equation are adapted to the film's geometry. The dynamic air film’s behavior study in supersonic regime requires a shock capturing scheme called WENO scheme (“Weighted Essentially Non Oscillatory”), mainly used in shock and turbulence studies. The numerical results give the film behavior modelling of a fixed air thrust bearing pad. The evolution of the quantities shows that shock wave can occur in a thin film.

1. Introduction
Aerodynamic thrust bearings are mechanical tribological devices which use relative sliding to support axial loads on a rotor. They are used today on a wide scale of turbomachinery at higher and higher speeds, possibly operating in the supersonic flow regime [1]. In this paper, we seek to study this regime of behavior of a thin film of air within an aerodynamic thrust bearing. The question of a supersonic regime in thin films remains open and its study is found at the interface between two scientific domains. In effect, lubrication is based on the solution of Reynolds equation [2], which does not take into account a number of phenomena. On the other hand, compressible fluid dynamics is based on the solution of the Navier-Stokes equations [3], which in the compressible case is not well adapted to the study of thin films, but does take into account diverse phenomena. It is therefore important to choose the best approach to the study of aerodynamic bearings.
Clearly, a balance is required to include the most important physical phenomena, but also, it is necessary to obtain efficient numerical resolution of the governing equations used. We present a numerical approach, solution of the Navier-Stokes equations adapted to thin film flow. The schematic drawing of figure 1 illustrates a typical configuration of a thrust bearing in a rotational geometry. The pad is fixed and faces an opposing rotating disk to resist axial forces generated within the machine. When the rotor is moving, a film of air is entrained between the two discs to establish the lubrication effect. In practice, the bearings may possess surfaces consisting of a deformable bump foil. However, in this study, for simplicity, and to focus on the fluid mechanics, the surfaces are considered rigid.

![Figure 1. Schematic of the dual profile aerodynamic thrust bearing.](image)

2. The Navier-Stokes equations adapted for thin film flow
The Navier-Stokes equations and the equation of energy are dimensionless as in [4], with the exception of the pressure. Pressure will no longer be nondimensionalized by a viscous term but rather by a dynamic inertia-based term [5]:

\[
\bar{p} = \frac{p}{\rho \mu^2_0}.
\]

This system, orders terms according to the geometric aspect ratio \(\varepsilon=H/L\). All the terms are retained and the system appears in the following vector form:

\[
\frac{\partial \mathbf{q}}{\partial t} = -\frac{\partial \mathbf{F}}{\partial x} - \frac{\partial \mathbf{G}}{\partial x} + \frac{\partial \mathbf{F}_{\text{visc}}}{\partial x} + \frac{\partial \mathbf{G}_{\text{visc}}}{\partial y}.
\]

The terms are separated into three classes according to their nature. The vector \(\mathbf{q}\) represents the vector of variables evolving over time. Vectors \(\mathbf{F}\) and \(\mathbf{G}\) are the Euler vectors that contain nonlinear inertia terms. The \(\mathbf{F}_{\text{visc}}\) and \(\mathbf{G}_{\text{visc}}\) vectors combine all terms related to the viscosity. The various expressions are,

\[
\mathbf{q} = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ E_t \end{bmatrix}, \quad \mathbf{F} = \begin{bmatrix} \rho u \\ \rho u^2 + p \\ \rho u v \\ (E_t + p) u \end{bmatrix}, \quad \mathbf{G} = \begin{bmatrix} \rho v \\ \rho u v \\ \rho v^2 + p \\ (E_t + p) v \end{bmatrix},
\]

\[
\mathbf{F}_{\text{visc}} = \begin{bmatrix} 0 \\ \varepsilon^2 \sigma_{11} \\ \varepsilon^2 \sigma_{12} \\ \varepsilon^2 (\sigma_{11} + \sigma_{12} v + q_1) \end{bmatrix}, \quad \mathbf{G}_{\text{visc}} = \begin{bmatrix} 0 \\ \sigma_{12} \\ \varepsilon^2 \sigma_{22} \\ \sigma_{12} v + \varepsilon^2 \sigma_{22} v + q_2 \end{bmatrix},
\]

(3) (4)
The deformation tensor is expressed in terms of the geometric ratio $\varepsilon$ which represents the ratio of thickness on contact length:

$$
\sigma_{11} = \frac{\mu}{\varepsilon Re} \left( \frac{2}{3} \frac{\partial u}{\partial x} - \frac{2}{3} \frac{\partial v}{\partial y} \right),
\sigma_{12} = \frac{\mu}{\varepsilon Re} \left( \frac{\partial u}{\partial y} + \varepsilon^2 \frac{\partial v}{\partial x} \right),
\sigma_{22} = \frac{\mu}{\varepsilon Re} \left( \frac{2}{3} \frac{\partial v}{\partial y} - \frac{2}{3} \frac{\partial u}{\partial x} \right)
$$

(5)

The heat source and total energy terms are given by the following formulas:

$$
Q_i = \frac{1}{(\gamma - 1) M_r^2} \frac{1}{\varepsilon Re Pr} \frac{\partial T}{\partial x_i},
$$

(6)

$$
E_i = \frac{p}{\gamma - 1} + \frac{1}{2} \rho \left( u^2 + \varepsilon^2 v^2 \right),
$$

where $Pr$ is the Prandtl number and $\gamma$ is the ratio of specific heats. The reference Mach number defined by

$$
M_r^2 = \frac{u_0^2}{\gamma R T_0},
$$

(7)

and $R$ is the perfect gas constant. These equations do not neglect viscous terms, and since the phenomena sought are of large physical scale (shocks waves, expansion waves, etc.), a turbulence model is initially not essential. Subsequently, such a model may be integrated into the system to capture smaller scale phenomena (turbulent vortices, etc.).

This system is suitable for thin films since the nondimensionalization allows the geometrical characteristics of the problem to be taken into account. The method also allows the use of a mesh with the same degree of discretization in the length and thickness. Each term of the equations sees its contribution weighted by $\varepsilon$ and thus flows are deformed to match the actual geometry.

These equations are solved using finite differences. The time contribution is discretized using an explicit Runge Kutta 4 scheme. The nonlinear terms are discretized using a shock-capturing scheme with the acronym WENO3 [6], [7], [8] (the Weighted Essentially Non-Oscillatory scheme). The viscous terms are discretized using a central differencing method of order two.

The boundary conditions for this system are that the pressure and density are imposed at the entry, the velocity $u = 0$ at the pad and $u = 1$ on the rotor, and the pressure is imposed at the exit output only if the flow is subsonic.

3. Results and Discussion

The geometrical configuration studied is as follows: the pad length $L = 2.5$ cm, the maximum to minimum ratio film thickness is 1.5, and the length of the inclined ramp is half of the total length of the pad. These data are portrayed in figure 2 below.

![Figure 2. Schematic configuration of the bearing double profile studied.](image)

Looking at the theory of supersonic flows, a well-known effect appears when a supersonic flow along a wall meets a wall change in direction (figure 3). Depending on the angle of the turn, either a shock wave or a series of expansion waves may occur as shown in the following figure. Through these
phenomena, the variables (such as pressure) sometimes evolve abruptly as portrayed in the above figures.

Figure 3. Direction change at the wall creating shock or expansion behaviour.

There appears to be no information in the tribology literature that may help, the behaviour of the fluid in the supersonic regime is quite different from the lower speed case. It is interesting to note under what conditions shock and expansion wave phenomena may occur. We conduct a study on the influence of the geometrical aspect ratio $\varepsilon$. For the same geometric shape, this factor is gradually increased, by changing the entry and output height film thickness to keep the same inclination. The slider surface is 4 cm in length and the tilt point lies in the middle, see figure 2. The ratio of the height at the input to the output is one half. The results are given for different values of $\varepsilon$ in the following figure 4.

Several remarks can be made about these results. Three regimes are distinguished on the basis of the value of the height to length ratio $\varepsilon$.

- A first regime corresponding to a lubrication flow occurs for values of $\varepsilon$ less than 0.1, figures 4 (a) and (b). The properties of this case are a constant pressure field across the gap, a maximum pressure greater than the pressure at the inlet, and the absence of shock or expansion wave phenomena.
- A second regime corresponding to a transition phase occurs for values of $\varepsilon$ ranging from 0.1 to 0.24, Figs 4 (c) and (d). This regime is distinguished by a varying pressure field across the gap, a maximum pressure near the moving wall, and the absence of shock or expansion phenomena.
- The third regime corresponds to shock flow for values of $\varepsilon$ greater than 0.24. The properties of this regime are the following: the pressure varies across the gap, a shock is present at the entry creating a very strong compression, Figs 4 (e)-(h). Expansion waves appear at the change of inclination of the pad creating a strong decrease of the pressure. It can also be noted that the shock increasingly tilts as the value of $\varepsilon$ increases.

These findings are consistent with theories of supersonic flows. Below $\varepsilon = 0.1$ the results are close to those of classical boundary layer theory, dissipating the shock phenomena. It is interesting to observe this transition by keeping the same number of discretization points.

In addition, looking at the influence of the nonlinear terms present in the Navier-Stokes system, it would seem that the following term (in bold) is the one responsible for the disappearance of the shock with decreasing $\varepsilon$.

$$ F = \begin{pmatrix} \rho u \\ \rho u^2 + p \\ \varepsilon^2 \rho uv \\ (E + p)u \end{pmatrix}, $$

(8)

This term should be predominant in the convergent part of the pad to allow for the appearance of the shock. However, its contribution is greatly diminished due to the geometric factor, and for this reason, there appears to be no shock in this geometry in thin film.
These results are only meant to scratch the surface in revealing the complete nature of shock behaviour in thin film high speed compressible lubrication. The film thickness is very high in the Figures 4(c) to ‘(h) and thus the Reynolds equation is no longer applicable for such configurations. Indeed, this study must also be conducted on geometries with a greater degree of convergence, different bearing numbers, and also for other shapes than the double profile. It is still possible that shock phenomena may appear in thin films and this will be the continuation of the further study.

Figure 4. Pressure versus position near the exit. Influence of the geometric ratio $\varepsilon$ on the occurrence of shock and expansion waves.
4. Conclusions
The study of an aerodynamic thrust bearing in a supersonic regime poses a choice of approaches to be taken. The chosen approach is suited to addressing supersonic behaviour, being based on the fundamental equations. The advantage of this approach is that the terms are weighted by the geometric aspect ratio $\varepsilon$ factor (ratio of gap height to length), allowing study of the system in a computational domain comprising the same number of discretization points in both directions.

The results show that inertia plays a role that is predominant on the behaviour of the fluid, strongly increasing the maximum pressure. The influence of the geometric ratio parameter is able to show the transition between a lubricated and a supersonic shock regime.

It should be noted that the absence of shock or expansion waves in these results is not an absolute certainty, indeed only one type of geometry has been studied. The possibility of the presence of shock phenomena in thin films is not entirely excluded, and one should study other geometries such as more severe convergence, bearing numbers and other pad shapes (such as the Rayleigh step, for example).

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