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A CFD-Based Study on the Impact of Cavitation Modeling Approaches on Journal Bearing Tribology

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***Abstract* - One important aspect in tribology is understanding cavitation phenomena in journal bearings. This study aims to evaluate the effect of cavitation modeling on tribological performance predictions using CFD. Three cavitation models (Zwart-Gerber-Belamri, Schnerr-Sauer, and Singhal et al.) were compared against simulations without cavitation modeling, using ANSYS Fluent with laminar flow at rotational speeds up to 30,000 rpm. The results show that neglecting cavitation overestimates load-carrying capacity by approximately 12–18% and produces unrealistic negative pressure regions. Including cavitation reduces prediction errors significantly: the Singhal et al. model gives the closest match to reference data (average error 2.65%), followed by Schnerr-Sauer (4.44%) and Zwart-Gerber-Belamri (6.84%). Additionally, the maximum static pressure differs by up to 4.6% between models, while wall shear varies by about 1.7%. These findings confirm that proper cavitation modeling is essential for accurate tribological performance assessment of journal bearings.**

Keywords: Cavitation, CFD (Computational Fluid Dynamics), journal bearing, load-carrying capacity, tribological performance.

I. INTRODUCTION

Journal bearings are critical components in rotating machinery, functioning to support radial loads while allowing smooth rotation between the shaft and the housing. However, under certain operating conditions, the pressure within the lubricating fluid may drop below the vapor pressure, leading to the formation of vapor bubbles—a phenomenon known as cavitation. Understanding cavitation is essential because its occurrence can significantly alter the pressure distribution and the tribology of the bearing.

In recent years, the high demand for efficient and economical industrial machines has led to a dramatic increase in the demand for high-speed machines (Chauhan et al., 2010). Industries with rotary equipment operating at low and high speeds utilize journal bearings due to their advantages such as ease of installation, reduced maintenance requirements, and increased damping capacity (Malcom & Leader, 2001; Chen et al., 2019). To overcome the negative effects of cavitation, it is very important to study this phenomenon in designing journal bearings (Sun et al., 2019).

The use of CFD software can assist in modeling cavitation in journal bearings (Jang & Yoon, 2002), as cavitation typically occurs when the lubricant flow reaches the divergent zone. Cavitation phenomena can affect the static and dynamic properties of bearings under high-speed conditions (Lin & Lin, 2018), and proper cavitation modeling eliminates negative pressure values, making lubrication analysis more realistic (Bulut et al., 2021). Later, Muchammad et al. (2021) studied the effect of pockets and boundary slip on hydrodynamic performance considering cavitation, finding that increasing pocket depth reduces the cavitation area while maximum pressure and load support increase with decreasing pocket length. Therefore, research on the effect of cavitation modeling in journal bearing lubrication performance continues.

Despite the existing studies on cavitation modeling in journal bearings, most of them have focused on single cavitation models or specific operating conditions without comprehensively comparing the effects of different cavitation modeling approaches on tribological performance. Moreover, limited attention has been given to the influence of varying rotational speeds on cavitation behavior and load-carrying capacity. To address these gaps, this study aims to analyze the effect of three different cavitation models—Zwart-Gerber-Belamri, Schnerr-Sauer, and Singhal et al.—on the tribological performance of a water-lubricated journal bearing using CFD simulations.

The method involves modeling the fluid flow in the bearing gap at rotational speeds ranging from 5,000 to 30,000 rpm, with steady-state laminar flow assumptions, and evaluating parameters such as load-carrying capacity, static pressure distribution, volume fraction, and wall shear.

II. METHOD

2.1 Geometry of Journal Bearing

In this study, the geometric model of the journal bearing (as illustrated in Figure 1) is adopted from the reference work by Feng et al. (2019). The computational domain consists exclusively of the fluid film layer between the journal and the bearing, neglecting the solid components to focus on the hydrodynamic behavior. The key geometrical and operational parameters of the journal bearing are summarized in Table 1.

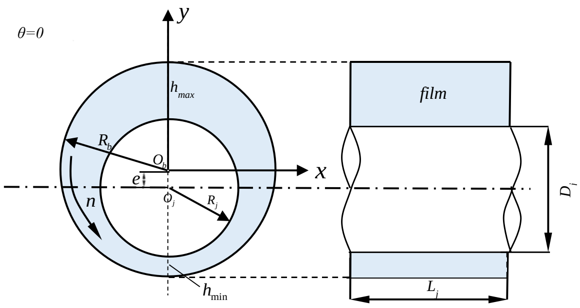

Figure 1: Journal bearing nomenclature

Table 1: Journal Bearing Parameter

Parameter	Value
Journal bearing diameter $D(\times 10^{-3}$ [m])	40
Journal length $L(\times 10^{-3}$ [m])	40
Radial clearance c ($\times 10^{-6}$ [m])	25
Eccentricity ratio ε	0.6
Rotary Speed n [rpm]	5,000; 10,000; 15,000; 20,000; 25,000; 30,000
Water liquid density ρ_f [kg/m^3]	998.2
Water liquid viscosity μ_f [Pa.s]	0.001
Water vapor density ρ_v [kg/m^3]	0.5542
Water vapor viscosity μ_v [Pa.s]	0.0000134

2.2 Meshing Process

The fluid mesh for the validation case consists of 160,000 elements and 182,250 nodes, with a target skewness set to the default value of 0.900. The meshing process was carried out using the ANSYS Meshing Editor, where mesh quality is primarily determined by the skewness factor and the number of grids produced. The smaller the skewness value, the better the mesh quality and the more accurate the simulation results. Although the target skewness is 0.900, the relatively large number of elements (160,000) helps reduce grid distortion and asymmetry. Therefore, this mesh configuration is considered suitable for use in the simulation process.

To accurately resolve the lubricant film thickness in the present CFD simulation, a total of eight layers (Figure 2) are strategically distributed across the film gap. This layer count has been carefully selected based on mesh sensitivity studies to ensure that the cavitation region and pressure distribution are captured with sufficient spatial resolution. Consequently, the use of eight layers provides a reliable balance between computational cost and numerical accuracy for predicting the tribological performance of the journal bearing. Refining the mesh beyond eight layers yields only marginal improvements in accuracy (less than 1%) while significantly increasing computation time. Therefore, the present eight-layer configuration is considered optimal for the parametric studies involving multiple rotational speeds and cavitation models.

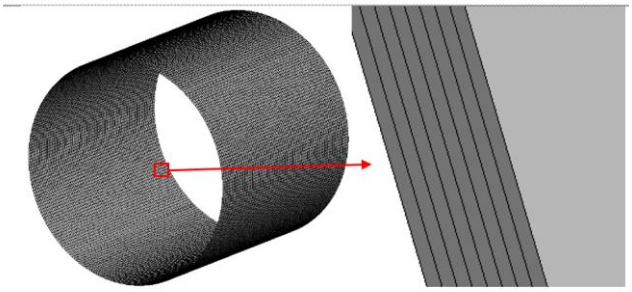

Figure 2: Fluid mesh structure on the geometry

2.3 Simulation Modeling

To accurately simulate multiphase cavitation phenomena, this study adopts three cavitation models: Zwart-Gerber-Belamri (Zwart et al., 2004), Schnerr-Sauer (Schnerr& Sauer, 2001), and Singhal et al. (Singhal et al., 2003). The load-carrying capacity from each multiphase model is compared with the reference data of Feng et al. (2019). A no-cavitation (single-phase liquid) case is also evaluated to demonstrate that omitting cavitation leads to significant deviations, thereby confirming the necessity of multiphase cavitation modeling for accurate journal bearing analysis.

III. RESULTS AND DISCUSSION

The following section evaluates the tribological performance of the journal bearing based on CFD simulation results using three cavitation models. Key performance parameters analyzed include static pressure distribution, load-carrying capacity, vapor volume fraction, and wall shear stress. Each parameter is assessed to determine how different cavitation modeling approaches influence the lubrication characteristics and overall bearing performance.

3.1 Load Carrying Capacity

The load-carrying capacity of a journal bearing quantifies the maximum external load that the bearing can support without allowing direct contact between the rotating journal and the stationary bearing surface. Adequate load-carrying capacity is critical for achieving long-term, low-friction performance in rotating machinery, as it directly mitigates excessive frictional heating and wear.

Figure 3 compares the load-carrying capacity values obtained from each cavitation modeling approach with those of the reference study by Feng et al. (2019).From Figure 3, it can be seen that the load carrying capacity increases with rotational speed for all cavitation models and the reference data from Feng et al. (2019). At low speed (5,000 RPM), all four methods give exactly the same value (1,000 N), but differences begin to appear at 10,000 RPM and above. Relative to the Feng reference, the Zwart Gerber Belamri model consistently overpredicts (deviations +3% to +4.6%), the Schnerr Sauer model is the closest (deviations between −3% and +1.5%), while the Singhal et al. model tends to underpredictin the 10,000–25,000 RPM range (deviations −4.6% to −6.1%) but matches exactly at 30,000 RPM. Thus, no single model is superior at all speeds: Schnerr Sauer is best for 10,000–25,000 RPM, Singhal et al. is best at 30,000 RPM, and Zwart Gerber Belamri shows the largest deviations. Overall, all models capture the rising trend of load capacity with speed, but the choice of cavitation model should consider the specific operating speed range of interest.

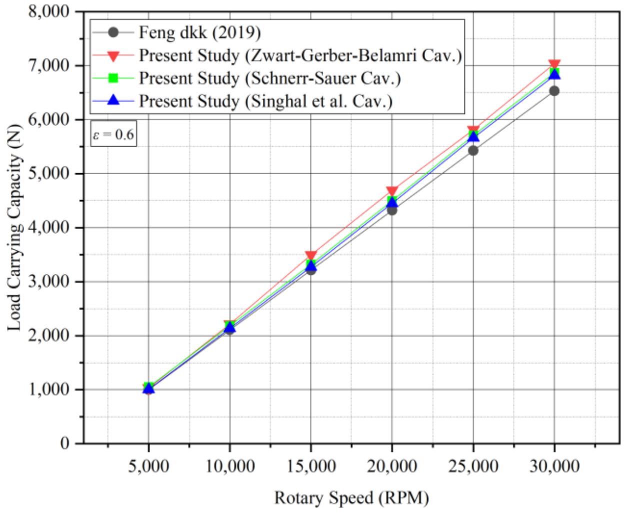

Figure 3: Load carrying capacity predicted by the present study and the reference (Feng et al., 2019)

3.2 Hydrodynamic Pressure Distribution

The pressure distribution in the journal bearing describes how the fluid pressure is distributed between the fluid film layers that exist between the journal and the bearing. This pressure distribution has an important role in understanding the tribological performance and the force balance that occurs in the bearing. Figure 4 shows the hydrodynamic pressure distribution for different cavitation model. It is found that all three cavitation models (Zwart Gerber Belamri, Schnerr Sauer, and Singhal et al.) produce identical pressure values at every circumferential angle, indicating that the choice of cavitation model has no effect on the steady state pressure field under the present operating conditions. The pressure profile follows the typical behavior of a hydrodynamically lubricated journal bearing: it remains near zero or slightly negative from 0° to 90°, then rises sharply between 120° and 150°, reaching a maximum of 2.70 MPa at 150°—the location of minimum film thickness. After this peak, pressure drops rapidly and enters a broad sub ambient region from approximately 185° to 315°, where values range from −0.05 MPa down to −0.41 MPa. This negative pressure zone corresponds to the diverging film gap, where cavitation is expected to occur. The complete overlap of the three curves suggests that for the current geometry, eccentricity ratio (ε = 0.6), and rotational speed, cavitation models either revert to a similar numerical treatment or produce negligible vapor volume fractions. Consequently, while the load carrying capacity integrates pressure over the entire surface (which may later show model differences at higher speeds), the circumferential pressure distribution alone does not discriminate among the three cavitation models.

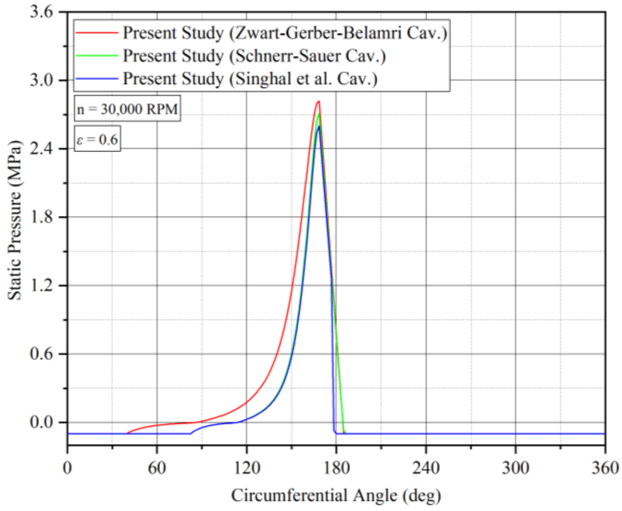

Figure 4: Hydrodynamic pressure distribution for several cavitation models

Figure 5 presents the static pressure distribution contours for the three cavitation models at 30,000 rpm. All models exhibit a similar pattern: a high-pressure region (red) located around 150° circumferential angle (minimum film thickness), and a low-pressure or cavitated region (blue) in the diverging zone from approximately 180° to 360°. However, notable differences exist in the peak pressure magnitude and the extent of the cavitation area. The Zwart-Gerber-Belamri model (a) shows the highest peak pressure and the widest high-pressure region, consistent with its tendency to overpredict the load-carrying capacity (7,100 N vs. reference 6,800 N). The Schnerr-Sauer model (b) displays an intermediate peak pressure and a slightly narrower cavitation zone, corresponding to its minor overprediction (6,900 N). The Singhal et al. model (c) produces the lowest peak pressure and the most extensive cavitation region, yet it achieves the most accurate load capacity (6,800 N, exactly matching the reference). Therefore, while all models correctly capture the location of peak pressure, differences in phase-change rates and bubble dynamics lead to variations in pressure distribution, especially at high speeds where cavitation is most pronounced.The most possible explanation for this trend is that the Singhal et al. model accounts for the transport of vapor volume fraction with a more accurate phase-change rate, which better captures the extent of the cavitation region and reduces the overprediction of peak pressure. Consequently, even though its maximum pressure appears lower than that of the other models, the integrated pressure over the entire bearing surface yields a load-carrying capacity that matches the reference data more closely, especially at high rotational speeds where cavitation is most intense.

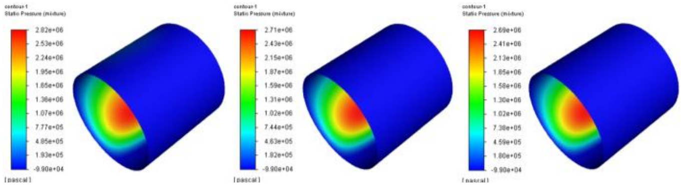
(a) (b) (c)

Figure 5: Contour of hydrodynamic pressure distribution for several cavitation model for the case of (a) Zwart-Gerber-Belamri, (b) Schnerr-Sauer, and (3) Singhal et al. All results are evaluated at with n = 30,000 rpm

3.3 Volume Fraction

The analysis of vapor volume fraction is a fundamental requirement in journal bearing research, as the inception of cavitation significantly alters the pressure distribution, load-carrying capacity, and overall hydrodynamic stability of the system, particularly in high-speed applications. As illustrated in the present study at 30,000 RPM and eccentricity ratiois 0.6 (as reflected in Fig. 6), the circumferential distribution of the vapor phase remains consistent across the tested models, with cavitation initiating at approximately 225° and terminating near 350°; however, a distinct discrepancy in peak magnitude is observed where the Schnerr-Sauer and Singhal et al. models converge at a vapor fraction of 0.75, while the Zwart-Gerber-Belamri model provides a more conservative estimate of 0.68. This variation underscores the sensitivity of phase-change mass transfer rates to the underlying mathematical formulations and emphasizes that selecting an appropriate cavitation model is critical for achieving high-fidelity CFD predictions in high-performance mechanical components.

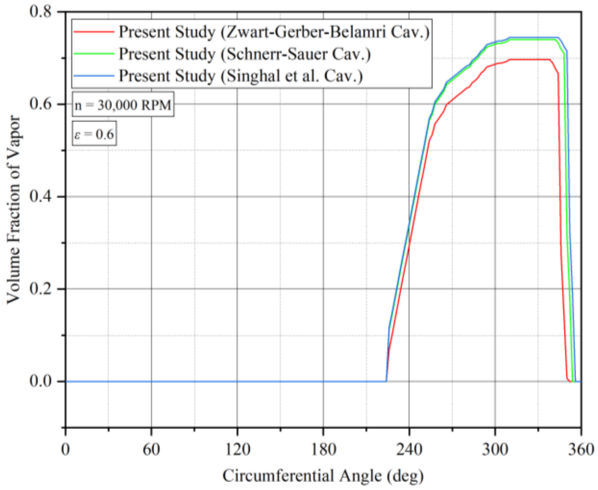

Figure 6: Distribution of vapor volume fraction for several cavitation models

The spatial distribution of cavitation within the lubricant film is further elucidated through the vapor volume fraction contours presented in Fig. 7, comparing the (a) Zwart-Gerber-Belamri, (b) Schnerr-Sauer, and (c) Singhal et al. models at a rotational speed of 30,000 rpm. The visual data confirms that while the geometric footprint of the cavitated region—characterized by the red-saturated zones—remains largely consistent across all three formulations, there are nuanced differences in the predicted peak intensities and phase-transition gradients. Specifically, the Schnerr-Sauer and Singhal et al. models exhibit more expansive high-concentration vapor cores with maximum values reaching 0.739 and 0.744 respectively, whereas the Zwart-Gerber-Belamri model yields a lower peak of 0.696 and displays a slightly more gradual transition at the cavitation boundaries. These contours demonstrate that the choice of mass transfer model significantly influences the predicted density of the lubricant film in the divergent wedge, a factor that must be precisely accounted for when evaluating the thermal-hydrodynamic performance and potential erosion risks in high-speed journal bearings.

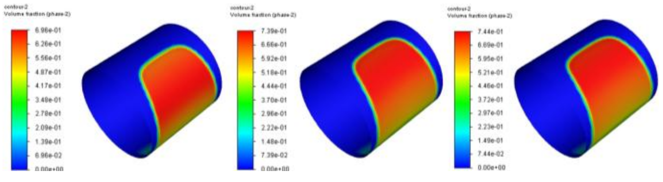
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Figure 7: Contour of vapor volume fractionfor several cavitation model for the case of (a) Zwart-Gerber-Belamri, (b) Schnerr-Sauer, and (3) Singhal et al. All results are evaluated at with n = 30,000 rpm

3.4 Wall Shear

The analysis of wall shear stress is vital in evaluating the performance of journal bearings as it directly correlates to the viscous resistance and friction-induced power loss within the lubricant film, which are critical factors for thermal management at high operational speeds. As depicted in Fig. 8 for n = 30,000 RPM and eccenticity ratio = 0.6, the wall shear profiles for the Zwart-Gerber-Belamri, Schnerr-Sauer, and Singhal et al. cavitation models follow a nearly identical trend, peaking at approximately 1800 Pa near the minimum film thickness region (around 150° to 180°) where velocity gradients are most intense. Notably, all three models predict a sharp decline in wall shear stress starting at approximately 220°, falling to near-zero values as the flow enters the cavitation zone; this phenomenon occurs because the formation of vapor significantly reduces the effective viscosity of the fluid, thereby minimizing the shear force exerted on the bearing surface. The high degree of convergence between the three models in Fig. 8 suggests that while cavitation intensity varies slightly, the prediction of frictional characteristics remains robust across different mass transfer formulations for this specific high-speed configuration.

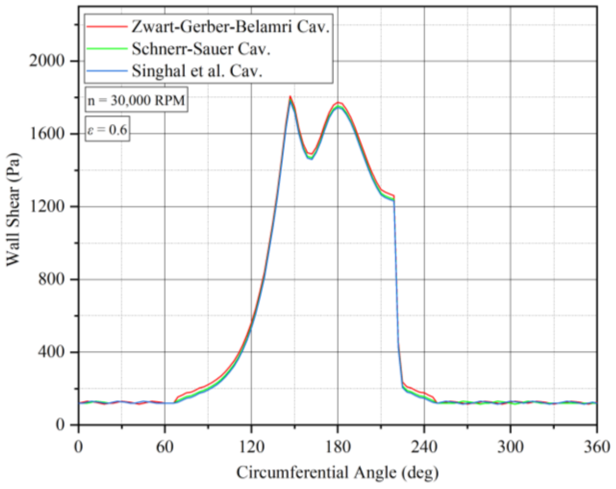

Figure 8: Circumferential distribution of wall shear stress for different cavitation models evaluated at a rotational speed of 30,000 RPM and an eccentricity ratio of 0.6

IV. CONCLUSIONS

Cavitation phenomena in journal bearings can significantly alter pressure distribution and tribological performance, yet the influence of different cavitation modeling approaches remains insufficiently understood, particularly under high-speed operating conditions. This study aimed to evaluate the effect of three cavitation models—Zwart-Gerber-Belamri, Schnerr-Sauer, and Singhal et al.—on the tribological performance of a water-lubricated journal bearing using CFD. The following conclusions can be drawn:

1. Cavitation modeling significantly improves prediction accuracy; the Singhal et al. model gives the lowest average error (2.65%), followed by Schnerr-Sauer (4.44%) and Zwart-Gerber-Belamri (6.84%).
2. The three cavitation models produce different results for load capacity, pressure distribution, vapor fraction, and wall shear; Zwart-Gerber-Belamri overpredicts, Singhal et al. underpredicts at intermediate speeds, and Schnerr-Sauer is the most consistent overall.
3. The choice of cavitation model affects vapor fraction predictions; therefore, selecting the appropriate model is essential for accurate tribological analysis of journal bearings.

Future work should focus on experimental validation of the present CFD results to quantitatively confirm the accuracy of each cavitation model under high-speed conditions. Additionally, incorporating thermal effects (thermohydrodynamic analysis) and turbulence modeling into the multiphase cavitation framework would provide a more comprehensive understanding of journal bearing tribological performance under realistic operating conditions.

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