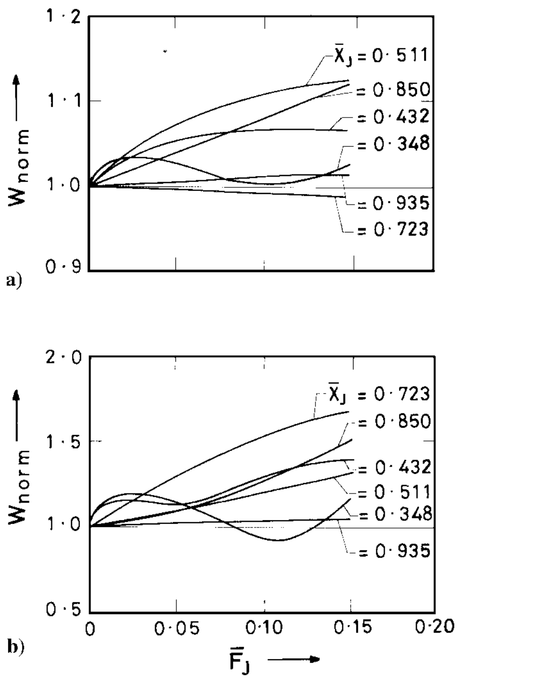

Fig. 3 Variation of w_{norm} with joint flexibility parameter $\bar{F}_j$ for a) root impulse and b) tip impulse.

disturbance structurally more critical than a control impulse of the same magnitude.

Conclusions

The present study has investigated the problem of the elastic response of a generic space vehicle with degraded joints. The stepped-beam formulation based on elementary beam theory is employed for extracting modal parameters of a normalized generic space vehicle. Next, the modal superposition principle is used with a low damping value for obtaining the elastic response of the vehicle to impulse excitation.

The results for elastic displacement peaks are obtained for normalized rotational joint flexibilities of different magnitudes acting at different spanwise locations. The results show that locations of the joint with flexibility play an important role in determining the magnitude and location of the peak response. Further, it is found that first mode frequency results for various values and locations of joint flexibilities can possibly be unified into a single linear expression, based on the normalized stiffness distribution of the space vehicle. Finally, it is found that tip excitation is more critical than root excitation.

Acknowledgment

The work reported forms a part of investigations carried out for project IDYMOD-1, funded by the Structures Panel (AR&DB), Ministry of Defence, of the Government of India.

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Aerodynamics of a Spinning Cylinder in Rarefied Gas Flows

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Introduction

INCOMPRESSIBLE flows around spinning bodies of revolution were studied in detail years ago (see the reviews by Prandtl and Tietjens[1] and Lugt[2]). It was found that, in the case of potential flow, the lift generated on the body has an opposite direction to the vector $[\boldsymbol{\Omega} \times \boldsymbol{u}_\infty]$ (the Magnus effect), where $\boldsymbol{\Omega}$ is an angular rotation vector of the spinning body and $\boldsymbol{u}_\infty$ is a freestream flow velocity vector. In this flow regime, three types of the flow patterns past a spinning circular cylinder can be identified[1,2] by the value of the governing similarity parameter, which is the roll parameter $\Theta = \Omega D/2u_\infty$, where D is a diameter of a cylinder. The patterns depend on the location of the points of separation and attachment.

In unsteady flow of a viscous incompressible fluid, the flow pattern becomes a function of both the roll parameter and the Reynolds number.[2] At $Re < 1.3 \times 10^5$ and $\Theta < 0.5$, the Magnus force can become negative.[3]

In the case of free-molecule flow, a different result was observed in Refs. 4–6. The lift of the spinning body under the free-molecule flow conditions should be opposite to the vector of lift under the continuum incompressible (potential) flow conditions. The lift and drag coefficients C_y and C_x, respectively, can be calculated using the formulas[6]

$$\begin{aligned} C_y(\Theta) &= (\pi/2)\sigma_t\Theta, \qquad & C_x(\Theta) &= 0 \\ C_y &= C_y(0) + C_y(\Theta), \qquad & C_x &= C_x(0) + C_x(\Theta) \end{aligned} \tag{1}$$

where the parameter σ_t is the coefficient of accommodation of the tangential momentum. The lift and drag coefficients $C_y(0)$ and $C_x(0)$ in the nonspinning-cylinder case have been calculated by using the following expressions[7]:

$$C_y(0) = 0, \qquad C_x(0) = C_{x,i}(0) + C_{x,r}(0)$$

$$C_{x,i}(0) = \frac{\sqrt{\pi}}{S} e^{-(S^2/2)} \left\{ I_0\left(\frac{S^2}{2}\right) + \frac{1+2S^2}{2}\left[I_0\left(\frac{S^2}{2}\right) + I_1\left(\frac{S^2}{2}\right)\right]\right\} \tag{2}$$

$$C_{x,r}(0) = \frac{\pi^{3/2}}{4u_\infty\sqrt{h_r}}, \qquad S = \sqrt{\frac{\gamma}{2}}M_\infty, \qquad h_r = \frac{m}{2kT_r}$$

where M_∞ is the Mach number, S is the molecular speed ratio, γ is a ratio of specific heats, m is a mass of molecule, k is Boltzmann's constant, T is temperature, and I_0 and I_1 are modified Bessel functions. Subscripts i and r refer to incident and reflected molecules, respectively. The Cartesian coordinate x is in the direction of the freestream flow velocity vector, and the coordinate y is in the direction of the vector $[\boldsymbol{\Omega} \times \boldsymbol{u}_\infty]$.

Karr and Yen[4] showed that the effect of spin on drag is of second order in Θ, and the component of lift $C_y(\Theta)$ has been found to be proportional to Θ and is analogous to the Magnus effect with the opposite sign.[6] The expressions of the momentum characteristics can be found in Ref. 6.

Received Oct. 28, 1998; revision received Jan. 26, 1999; accepted for publication Jan. 27, 1999.

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In the present study, the aerodynamic coefficients of a spinning infinite cylinder have been evaluated numerically for a range of the two similarity parameters: Knudsen number Kn_D and spin rate Θ. The analysis of the coefficients of the spinning cylinder is based on the numerical results that were obtained using Bird's direct simulation Monte Carlo (DSMC) technique.[8,9] The results are compared with free-molecule flow data.[6]

DSMC Method

The DSMC method[8] has been used in this study as a numerical simulation technique for low-density gas flows. The flow parameters are calculated using a two-dimensional DSMC code.[9] Molecular collisions in argon are modeled using the variable hard sphere molecular model.[8] The gas–surface interactions are assumed to be fully diffusive with full energy and moment accommodation with $\sigma_t = 1$. The stagnation temperature is assumed to be equal to the wall temperature. The code validation was tested[8,10] in comparing numerical results with experimental data[10] for simple-shape bodies.

In the present calculations, one region is used, with a total of 2700 cells. The 29,800 molecules are unevenly distributed while providing an overall average of 11 molecules per cell. By following the recommendations of Refs. 8 and 9, reliable results are obtained for an average of at least 10 molecules per cell in the most critical region of the flow. In all cases, the usual criterion[8] for the time step Δt_m has been realized: $2 \times 10^{-7} \leq \Delta t_m \leq 1 \times 10^{-6}$ s. Under these conditions, aerodynamic coefficients and gasdynamics parameters have become insensitive to the time step. The location of the external boundary with the upstream flow conditions varies from $1.0D$ to $1.5D$ for different flow conditions. Calculations were carried out on a personal computer. The computing time of each variant was estimated to be approximately 10–40 h.

Results

Subsonic Rarefied-Gas-Flow Regime

At subsonic flow conditions, the speed ratio S becomes small, and the aerodynamic coefficients become very sensitive to the ratio magnitude.[7] In the present Note, the transition flow regime has been studied numerically at $M_\infty = 0.15$, $\gamma = \frac{5}{3}$ (argon gas), and $\Theta = 1$, 3, and 6.

The lift and drag coefficients are shown in Figs. 1 and 2, respectively. In the transition flow regime ($Kn_D > 0.03$), both the incident and reflected molecules significantly influence the lift. The incident molecules dominate when $Kn_D < 0.1$, and the reflected molecules dominate when $Kn_D > 0.1$. Under these conditions, the lift coefficient changes sign for the cylinder spinning in a counterclockwise direction, and the drag coefficient becomes a function of the spin rate. The values of $C_{y,r}$ and C_x at $Kn_D > 3$ are near the magnitudes of the lift $C_{y,fm}$ and drag $C_{x,fm}$ coefficients calculated from Eqs. (1) for the free-molecule flow.

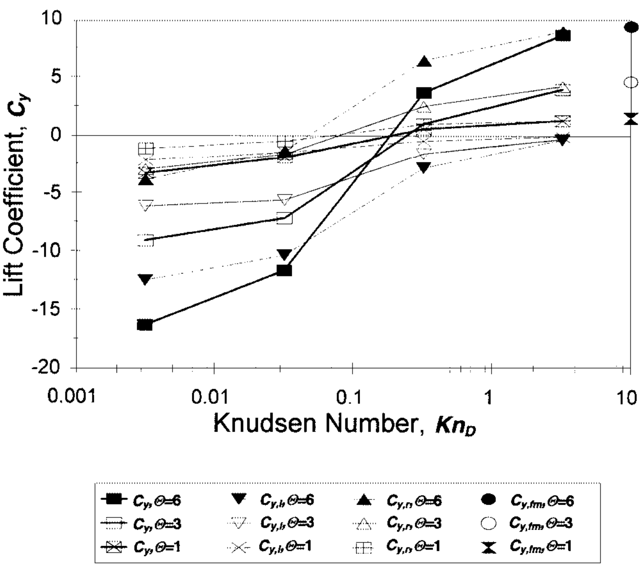

Fig. 1 Lift coefficient C_y of a spinning cylinder vs Knudsen number Kn_D at M_∞ = 0.15 and different spin rates: filled symbols, Θ = 6; open symbols, Θ = 3; and crossed symbols, Θ = 1.

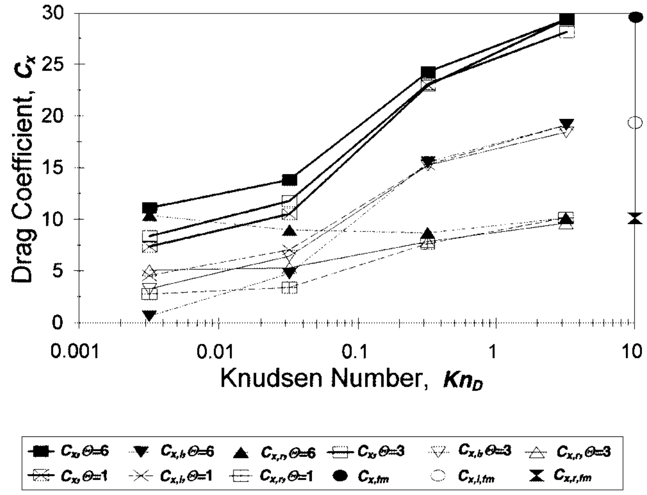

Fig. 2 Drag coefficient C_x of a spinning cylinder vs Knudsen number Kn_D at M_∞ = 0.15 and different spin rates: filled symbols, Θ = 6; open symbols, Θ = 3; and crossed symbols, Θ = 1.

The flowfield patterns near a spinning cylinder at near-free-molecule ($Kn_D = 3.18$) and near-continuum ($Kn_D = 0.032$) flow regimes were studied by Riabov.[11] The character of the flow is absolutely different in these cases. The zone of circulating flow is much wider in the continuum flow regime, and its width is comparable to the radius of a cylinder. In the near-free-molecule flow regime, the asymmetry of the flow in the upper and lower regions is significant. The major disturbances of the flow parameters are concentrated in the vicinity of the spinning surface. In the opposite case of the near-continuum flow regime, the spinning effect significantly changes the flow pattern in the area far from the surface. These differences in flow patterns dominate the character of molecule–surface interactions.

Supersonic Rarefied-Gas-Flow Regime

At supersonic flow conditions, the speed ratio S becomes large, and the aerodynamic coefficients become less sensitive to the ratio magnitude.[7] In the present study, the transition flow regime has been investigated numerically at $M_\infty = 10$, $\gamma = \frac{5}{3}$ (argon gas), and $\Theta = 0.03$ and 0.1.

The lift and drag coefficients are shown in Figs. 3 and 4, respectively. For the lift coefficient, the influence of reflected molecules is dominant in the transition flow regime ($Kn_D > 0.03$). The incident-molecule input becomes significant at Knudsen number $Kn_D < 0.1$. Under the considered flow conditions, the lift coefficient has a positive sign (which is opposite to the sign under the continuum flow regime) for the cylinder spinning in a counterclockwise direction. The drag coefficient is insensitive to the spin rate. Furthermore, the incident part of the drag coefficient $C_{x,i}$ predominates the magnitude of the total drag coefficient C_x. The values of C_y and C_x at $Kn_D > 4$ are near the magnitudes of the lift $C_{y,fm}$ and drag $C_{x,fm}$ coefficients calculated from Eqs. (1) for the free-molecule flow.

The flow characteristics are different in these cases.[11] For a small spin rate, $\Theta = 0.1$, the zone of circulating flow is located in the vicinity of the surface, and it does not affect significantly the flow zone located far from the surface.

In the case of near-continuum flow, the spinning effect slightly changes the flow pattern in the area far from the surface.[11] The flow pattern becomes asymmetrical in this case. These differences in flow patterns dominate the character of molecule–surface interactions, and they characterize the differences in the performance parameters under significantly distinct flow conditions (Figs. 3 and 4).

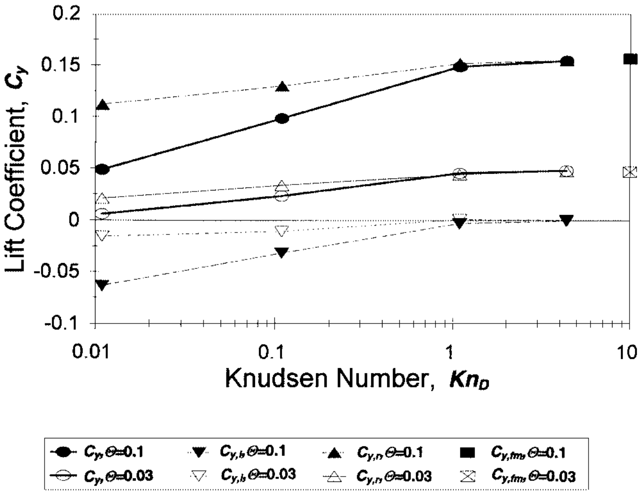

Fig. 3 Lift coefficient C_y of a spinning cylinder vs Knudsen number Kn_D at M_∞ = 10 and different spin rates: filled symbols, Θ = 0.1, and open symbols, Θ = 0.03.

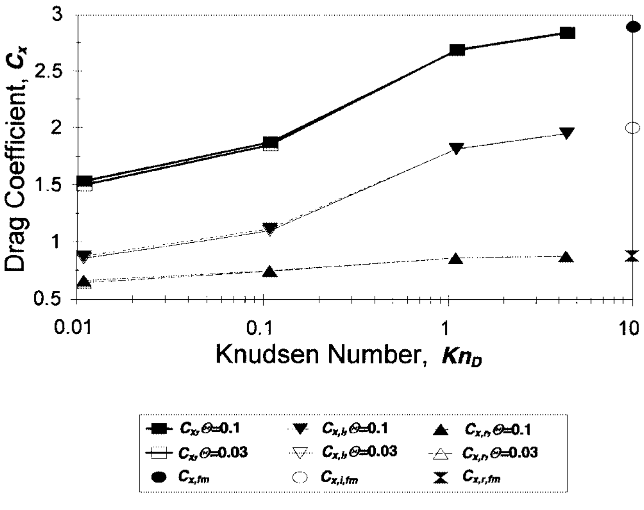

Fig. 4 Drag coefficient C_x of a spinning cylinder vs Knudsen number Kn_D at M_∞ = 10 and different spin rates: filled symbols, Θ = 0.1, and open symbols, Θ = 0.03.

Conclusions

The aerodynamic coefficients of a spinning infinite cylinder have been evaluated numerically for a range of two similarity parameters: Knudsen number and roll parameter. It has been found that the lift force on a spinning cylinder at subsonic upstream conditions has different signs in the continuum and free-molecule flow regimes. The location of the sign change is in the transitional flow regime near $Kn_D \sim 0.1$. The major factor of influence is the magnitude of momentum of the reflected and incident molecules, which depends on the value of the Knudsen number. The spinning parameter significantly influences the flow pattern around the cylinder as well as the force magnitude. At the supersonic upstream flow conditions, the lift coefficient has a positive sign in the transitional and free-molecular regimes (which is opposite to the sign under the continuum flow regime) for the cylinder spinning in a counterclockwise direction. The supersonic drag coefficient is insensitive to the spin rate, and the incident component dominates the magnitude of the total drag coefficient.

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