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Optimized Design of Finite Hydrodynamic Journal Bearing For Minimum Heat Loss Using Parameters Radius and Clearance by Application of Stochastic Geometric Programming

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ABSTRACT: *Optimization is the art of obtaining the best results under given circumstances. In design, construction and maintenance of any engineering system, the ultimate goal is either to minimize the effort required or to maximize the desired benefits. The various processes of optimization come under the subject Operation Research (O.R.). O.R. one of the branch of mathematics which is concerned which the application of scientific methods and techniques to design making problems and establishing optimal situations. In this project we aim to find the optimum design of a hydrodynamics bearing through operations research techniques. The two methods used are stochastic programming and geometric programming. The existing design procedure treats design variables as deterministic ones. In actual practice due to manufacturing tolerances etc. design variables do not remain deterministic but become probabilistic. The probabilistic nature of these should be given proper consideration while designing. This project deals with an approach which takes into account the probabilistic nature of designs variables, as well as probability of satisfying constraint equations. Stochastic signomial geometric programming has been used for optimization.*

I. INTRODUCTION

In this project aim is to find the optimum design of a hydrodynamic journal bearing through operations research techniques. The two methods used are “Stochastic Programming and Geometric programming”.

Stochastic or probabilities programming deals with situations where some or all the parameters of the optimization problems are described by stochastic (random or probabilistic) variable rather than by deterministic quantities. For instance, in the design of mechanical systems, the actual dimensions of any machine part has to be taken as a random variable since the dimension may lie anywhere within a specified (permissible) tolerance limit, stochastic programming thus, change a probabilistic problem to deterministic one.

This deterministic form of a problem is called a primal problem which is converted into a dual and solved by the geometric programming method

Theory

When some of the parameters involved in the objective function and constraints vary about their mean values, a general optimization problem has to be formulated as a stochastic nonlinear programming problem. Assuming that all the random variables are independent and follow normal distribution, a stochastic nonlinear programming problem can be stated in standard form as:

Find X which minimizes f(Y)

Subject to

$$P\left[g_j(Y) \geq 0\right] \geq p_j, j = 1, 2, \ldots \ldots \ldots \ldots m \quad (1)$$

Where Y is the vector of N random variables $y_1, y_2, \ldots \ldots \ldots \ldots y_N$ and it includes the decision variables $x_1, x_2 \ldots \ldots \ldots . x_n$. The case when X is deterministic can be obtained as a special case of the present formulation.

Objective Function

$$f(Y) \cong (\overline{Y}) - \sum_{i=1}^{N} \left(\frac{\partial f}{\partial y_i}\bigg|_{\overline{Y}}\right) \overline{y}_i + \sum_{i=1}^{N} \left(\frac{\partial f}{\partial y_i}\bigg|_{\overline{Y}}\right) y_i = \varphi(Y) \quad (2)$$

Further if Y_i(i = 1, 2, 3, …..n) follows a normal distribution Q(Y), Q(Y) also being a linear function of Y following a normal distribution, then the mean and variance of Q(V) will be

$$\overline{\varphi} = \varphi(\overline{Y}) \quad (3)$$

And

$$Var(\varphi) = \sigma_\varphi^2 = \sum_{i=1}^{n} \left(\frac{\partial f}{\partial y_i}\bigg|_{\overline{Y}}\right)^2 \sigma_{y_i}^2 \quad (4)$$

Since all y_i are independent. For the purpose of optimization a new objective function F(Y) can be constructed as

$F(Y) = k_1\overline{\varphi} + k_2\sigma_\varphi$ (5)

Where $k_1 \geq 0\ and\ k_2 \geq 0$ and their numerical values indicate the relative importance of $\overline{\varphi}$ and σ_φ for minimization.

Where k_1 and k_2 are constant having values ≥ 0, $k_2 = \phi$ indicates that the expected values of F(Y) is to be minimized ignoring the standard deviation. On the other hand $k_1 = 0$ indicates that one is interested in minimizing the variety of F(Y) about its mean value without bothering about the mean value of F(Y) $k_1 = k_2 = 1$ indicates that equal importance is given to the minimization of the mean as well as standard deviation

Taking $k_1 = k_2 = 1$

$F(Y) = \overline{\varphi} + \sigma_\varphi$

Conversion of probabilistic constraints into an equivalent deterministic form:

If some parameters are random in nature the constraints will also be probabilistic and one would like to have the probability that a given constraint is satisfied to be greater than a certain value. The constraints inequality can be written as

$\int_0^\infty f_{g_j}(g_j)d\,g_j \geq p_j$ (6)

Where $f_{g_j}(g_j)$ is the probability density function of the random variable g_j (a function of several random variables is also a random variable) whose range is assumed to be $-\infty\ to\ \infty$. The constraint function $g_j(Y)$ can be expanded around the vector of mean values of the random variables, $\overline{Y}$ as

$g_j(Y) \cong g_j(\overline{Y}) + \sum_{i=1}^{N}\left(\frac{\partial f}{\partial y_i}\bigg|_{\overline{Y}}\right)(y_i - \overline{y}_i)$ (7)

g_j can be obtained as

$\overline{g}_j = g_j(\overline{Y})$ (8)

And

$\sigma_{gj} = \left[\sum_{i=1}^{n}\left(\frac{\partial g_j}{\partial x_i}\bigg|_{\overline{Y}}\right)^2 \sigma_{y_i}^2\right]^{\frac{1}{2}}$ (9)

If $\emptyset_j(p_j)$ is standard normal variate corresponding to probability p_j, then using equations (6)-(9)

$\overline{g}_j - \emptyset_j(p_j) = \left[\sum_{i=1}^{N}\left(\frac{\partial g_j}{\partial y_i}\bigg|_{\overline{Y}}\right)^2 \sigma_{y_i}^2\right]^{\frac{1}{2}} \geq 0,\ j = 1, 2 \ldots\ldots m$ (10)

Thus the equivalent deterministic problem is to minimize F(Y) satisfying constraint equation.

Application: design of finite hydrodynamic journal bearing for minimum heat loss

Problem statement:

Optimization design of finite hydrodynamic journal bearing for minimum heat loss using parameters radius ($\overline{R}$) and clearance ($\overline{C}$)

Given that:-

L/D = 1.0, $\epsilon = 0.6$, $\overline{N}$ = 900 RPM

Data obtain from computer program using finite element method

f_x = 3.14570, $f_z = 3.14796$, $W = \sqrt{f_x^2 + f_z^2} = 4.95080$ N, $\emptyset = 50.1570, Q = 2.6894$

Sommerfield number(S) = 0.12858

$$f(Friction\ co-efficient\ factor) = \left[\frac{2\pi^2 S}{\sqrt{1-\varepsilon^2}} + \frac{\varepsilon}{2}sin\emptyset\right]\left(\frac{\overline{C}}{\overline{R}}\right)$$

$f = \left[\frac{2\pi^2 0.12858}{\sqrt{1-0.6^2}} + \frac{0.6}{2}\sin(50.5170)\right](0.001)$ = 0.00340 N (11)

Other data (assuming):-

Oil selected SAE 30

Operating temperature	-	40^0
Viscosity of oil ($\overline{\mu}$)	-	90 CPS or 0.09×10^{-6} N-sec/mm^2
Density of oil ($\overline{\rho}$)	-	0.9 Kg/mm^3
Specific heat of oil ($\overline{C}_p$)	-	1.88 Kj/kg^{0}C

$\overline{\theta}$ = 0.6666^0 m per unit length, $\overline{f}_s = 50 \times 10^6$ N/m^2, $\overline{G} = 8 \times 10^{10}$ N/m^2.

Formulation of the problem:

To design a journal bearing for minimum heat loss for the given data

N = 900 RPM $\quad\quad\mu$ = 0.09×10^{-6} N-sec/mm^2

From the Programme for the eccentricity ratio (ε) = 0.6

$\emptyset$ = 50.1570 $\quad\quad$ Q = 2.6894

Sommerfield number (S) = 0.12858 $\quad\quad f_x$ = 3.82110

f_z = 3.14796 $\quad\quad\rho$ = 0.9 Kg/mm^3

c_p = 1.88 Kj/kg^{0}C $\quad\quad\Delta t$ = 3.9 ^{0}C

Assuming $\frac{\overline{C}}{\overline{R}}$ = 0.001 from Machine Design's (V.B.Bhandari) Book

by calculating using the above values

$W(Load\ carring\ capacity) = \sqrt{f_x^2 + f_z^2} = \sqrt{3.82110^2 + 3.14796^2}$ = 4.95080 N

$U(Velocity) = \frac{2\pi\overline{R}N}{60} = \frac{2\pi 900\overline{R}}{60} = 94.2477$ mm/sec

$\omega(Angular\ velocity) = \frac{2\pi N}{60} = \frac{2\pi 900}{60} = 94.2477$ rad/sec

$$f(Friction\ co-efficient\ factor) = \left[\frac{2\pi^2 S}{\sqrt{1-\varepsilon^2}} + \frac{\varepsilon}{2}sin\emptyset\right]\left(\frac{\overline{C}}{\overline{R}}\right)$$

$f = \left[\frac{2\pi^2 0.12858}{\sqrt{1-0.6^2}} + \frac{0.6}{2}\sin(50.5170)\right](0.001)$ = 0.00340 N

To attain minimum heat loss we have to minimize the difference between heat generated and heat dissipated.

Thus our objective function can be defines as:-

To minimize –

$$F_1 = \overline{H}_g - \overline{H}_d$$

$$F_1 = \left[\frac{W\overline{\mu}\overline{\omega}\overline{R}^4}{\overline{C}^2}\right]f\overline{U} - Q\overline{\omega}\overline{C}\overline{R}^2\overline{\rho c_p}\Delta\overline{t} \quad (12)$$

Now putting the value in equation (4.1) and (4.2)

$$F_1 = \left\{\left[\frac{4.9507 \times 0.09 \times 10^{-6} \times 94.2477 \times \overline{R}^4}{\overline{C}^2}\right] \times 0.00340 \times 94.2477\overline{R}\right\} - \left\{2.6894 \times 94.2477 \times 0.9 \times 1.88 \times 3.9\ \overline{C}\ \overline{R}^2\right\}$$

$$F_1 = 1.34726 \times 10^{-5}\frac{\overline{R}^5}{\overline{C}^2} - 1672.59\overline{C}\overline{R}^2 \quad (13)$$

Constraint equation:

For any given bearing journal should be sufficiently strong so that it can transmit maximum torque for permissible values of θ the angle of twist, and f, the shear stress. For any length l, the maximum angle of twist is given by

$$\frac{\overline{G}\theta}{\overline{l}} = \frac{\overline{f_s}}{\overline{R}} \quad (14)$$

For G is the modulus of rigidity,

To avoid the failure of the journal due to torque transmission, the actual angle of twist and shear stress must be less than permissible value, i.e.

Hence the constraint equation is

$$g_j = \frac{\overline{G}\theta\overline{R}}{\overline{l}\overline{f}_s} \le 1 \quad (15)$$

If the design parameters $\overline{R}$ and $\overline{C}$ are taken as random variables because of manufacturing tolerances etc, their values will fluctuate about mean values. If these random variables follow normal distribution and the mean values and standard deviation are $\overline{R}$ and $\overline{C}$ and σ_R and σ_C then the new objective function in deterministic form is given by equation as

$$\sigma_{gj} = \left[\sum_{i=1}^{n}\left(\frac{\partial g_j}{\partial x_i}\right)^2 \sigma^2 y_i\right]^{\frac{1}{2}} \quad (16)$$

By simplification

$$\sigma_{gj} = F_1 + \left\{\sum_{i=1}^{n}\left(\frac{\partial F_1}{\partial R}\right)^2 \sigma_R^2\right\}^{\frac{1}{2}} \quad (17)$$

If the constraint equation g_j is satisfied with a probability p_j if the normal variate for probability p_j is given $\emptyset_j(p_j)$ then, the new constraint equation in deterministic form is given in equation as

Finally problem reduces to minimize the objective function given by equation satisfying constraint equation.
If the design parameters $\overline{R}$ and $\overline{C}$ are taken as random variables following normal distribution and the standard deviations are $\sigma_R = 0.01\overline{R}$ and $\sigma_C = 0.01\overline{C}$ respectively, then the new objective function in deterministic form, from equation is

$$F_d = \left\{1.34726 \times 10^{-5}\frac{\overline{R}^5}{\overline{C}^2} - 1672.59\overline{CR}^2\right\} + \left\{6.7363 \times 10^{-7}\frac{\overline{R}^5}{\overline{C}^2} - 33.4518\overline{CR}^2\right\} + \left\{-2.69452 \times 10^{-7}\frac{\overline{R}^5}{\overline{C}^2} - 16.7259\overline{CR}^2\right\}$$

$$F_d = 1.3878 \times 10^{-5}\frac{\overline{R}^5}{\overline{C}^2} - 1722.7677\overline{CR}^2 \quad (18)$$

On substituting assumed data in equation

$$g_j = \frac{8 \times 10^{10} \times 0.6666\pi \times \overline{R}}{10^3 \times 50 \times 10^6 \times 180} \leq 1$$

$$g_j = 18.6168 \times 10^{-3}\overline{R} \leq 1 \quad (19)$$

If the constraint equation is satisfied with a probability of 99.99%, then for P_j = 99.99% the normal variate $\emptyset_j(P_j)$ from table no. 3.1. Using equation the constraint equation in deterministic form is

$$g_j d = 18.6168 \times 10^{-3}\overline{R} - 5\left[(18.6168 \times 10^{-3})^2\left(0.01\overline{R}\right)^2\right]^{\frac{1}{2}}$$

$$g_j d = 0.01767\,\overline{R} \leq 1 \quad (20)$$

Hence the problem reduces to minimize objective function given by equation satisfying constraint equation.

Application of geometric programming:

For the project problem we have obtained "primal function" as

$$F_d = 1.3878 \times 10^{-5}\frac{\overline{R}^5}{\overline{C}^2} - 1722.7677\overline{CR}^2$$

Subject to

$g_j d = 0.01767\,\overline{R} \leq 1$

In this problem

n = Number of primal variables = 2
m = Number of primal constraint =1
N_o = Number of terms in objective function = 2
N_1 = Number of terms in constraint equation = 1
N = Total number of terms in the posynomials = N_o+N_1 = 3

$$\lambda_{01} - \lambda_{02} = 1 \quad (21)$$

$$a_{011}\lambda_{01} + a_{012}\lambda_{02} + a_{111}\lambda_{11} = 0$$

$$a_{021}\lambda_{01} + a_{022}\lambda_{02} + a_{121}\lambda_{11} = 0$$

$$\lambda_{oj} \geq 0, j = 1, 2, 3$$

$$\lambda_{11} \geq 0$$

Comparing from the matrix

$$\begin{bmatrix} a_{011} & a_{012} & a_{0111} \\ a_{021} & a_{022} & a_{0121} \end{bmatrix} = \begin{bmatrix} -2 & -1 & 0 \\ 5 & -2 & 1 \end{bmatrix} \quad (22)$$

So now we have

a_{011} = -2 a_{012} = -1 a_{0111} = 0
a_{021} = 5 a_{022} = -2 a_{0121} = 1
C_{01} = 1.3878×10^{-5}
C_{02} = 1722.7677
C_{11} = 0.01767

By putting all these values in equation and finding the values of $\lambda_{01}, \lambda_{02}\, and\ \lambda_{03}$

$$\lambda_{01} - \lambda_{02} = 1$$

$-2\lambda_{01} - \lambda_{02} + 0 = 0$
$5\lambda_{01} - 2\lambda_{02} + \lambda_{11} = 0$
Than by solving the above equation we have
λ_{01} = 1/3 λ_{02} = -2/3 λ_{11} = -3
Now applying these values in equation i.e.

$$v(\lambda) = \left[\frac{c_{01}}{\lambda_{01}}(\lambda_{01}+\lambda_{02})\right]^{\lambda_{01}} \left[\frac{c_{02}}{\lambda_{02}}(\lambda_{01}+\lambda_{02})\right]^{\lambda_{02}} \left[\frac{c_{11}}{\lambda_{11}}(\lambda_{11})\right]^{\lambda_{11}}$$

$$v(\lambda) = v^* = x_0^* = \left[\frac{1.3878\ \times 10^{-5}}{1/3}(1/3-2/3)\right]^{1/3} \left[\frac{1722.7677}{-2/3}(1/3-2/3)\right]^{-2/3} \left[\frac{0.01767}{-3}(-3)\right]^{-3}$$

x_0^* = -48.1136
By applying the equation

$$\lambda_{02}^* = \frac{c_{02}(x_1^*)^{a012}(x_2^*)^{a022}}{x_o^*} \qquad (23)$$

$$\frac{-2}{3} = \frac{1722.7677(x_1^*)^{-1}(x_2^*)^{-2}}{-48.1136}$$

$$\frac{\lambda_{11}^*}{\lambda_{11}^*} = c_{11}(x_1^*)^{a0111}(x_2^*)^{a0121}$$

$$\frac{-3}{-3} = 0.01767(x_1^*)^0(x_2^*)^1$$

x_2^* = 56.5930 mm = $\overline{R}$

$$\frac{-2}{3} = \frac{1722.7677(x_1^*)^{-1}(56.5930)^{-2}}{-48.1136}$$

By solving above equation
x_1^* = 0.01676 mm = $\overline{C}$

II. RESULT

The different parameter can be selected to calculate objective function. First the speed is chosen for 1000 RPM then 1100 RPM and 1200 RPM and the viscosity of oil and temperature difference will remain constant. Next the viscosity of oil is chosen 0.09 then 0.10, 0.11, 0.12 and 0.13 and temperature difference and speed will remain constant. Then again the temperature difference is chosen 3.9 then 4.9, 5.9, 6.9 and 7.9 and speed and viscosity of oil will remain constant

Change in rotation of journal

N	$\overline{H}_g - \overline{H}_d$
900	5.9173 KN-m/sec
1000	7.32038 KN-m/sec
1100	8.872567 KN-m/sec
1200	10.6700 KN-m.sec
1300	12.4242 KN-m/sec

Change in viscosity of oil

$\overline{\mu}$	$\overline{H}_g - \overline{H}_d$
0.09	5.9173 KN-m/sec
0.10	6.5883 KN-m/sec
0.11	7.2593 KN-m/sec
0.12	7.9303 KN-m.sec
0.13	8.6014 KN-m/sec

Change in temperature difference

$\Delta\overline{t}$	$\overline{H}_g - \overline{H}_d$
3.9	5.9173 KN-m/sec
4.9	5.8860 KN-m/sec
5.9	5.8547 KN-m/sec
6.9	5.8235 KN-m.sec
7.9	5.7922 KN-m/sec

III. CONCLUSION

The non dimensional parameter for hydrodynamic journal bearing such as Sommerfield Number(S) Total flow (Q), FRC (f), and Attitude Angle (∅) for a hydrodynamic journal bearing were calculated using FEM technique for Eccentricity Ratio ε = 0.6, L/D = 1.0
The objective function was again calculated by the variation in the following ways:-
(i) By the variation in the value of speed (N). (ii) By the variation in the value of viscosity of oil ($\overline{\mu}$).
(iii) By the variation in the value of temperature difference ($\Delta\overline{t}$).
The representative charts are shown in figs (5.1, 5.2 and 5.3). The advantages of these charts are that one can read the value of objective function for any specified speed or temperature difference or viscosity. Similar charts can be prepared using the variation of the other parameters. These charts can be used for the design purpose so as to reduce the magnitude of the objective function by applying external agencies.

In the present work a numerical example has been solved, but this method can also be applied to any practical bearing if the information about the required data is available.

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