Lecture 28: Mechanical Design of Turbomachinery

Integration and Rotordynamics of Turbo Pumps

1. Integration and Mechanical Components

As noted before, turbines and pumps are often mounted on a common shaft. If the oxidizer and fuel have similar densities, their respective pumps can also be on one shaft. This is the case in the MK-3 Atlas and Delta II booster turbopump, which, however, has a geared turbine-pump transmission. The Russian RD-170 takes a further integration step by having a single turbine drive both, fuel and oxidizer pump, all on a single shaft. In addition, these pumps feed not a single thrust chamber, but a cluster of four in the case of the Energia vehicle (Fig 4, Lec. 24). Engines using LH fuel require different speeds for the oxidizer and fuel pumps. The first of these engines, the RL-10, had a single-stage oxygen pump on one shaft, gear driven by a second shaft on which were mounted a 2-stage hydrogen pump and the drive turbine. More recent engines (LE-7, SSME) feature separate shafts for the oxygen and fuel, each carrying its own drive turbine.

Bearing design and bearing placement have a significant impact on the overall turbopump characteristics. Existing engines use roller element bearings, and in recent designs, these are lubricated and cooled by the propellant being pumped, which simplifies the construction. On the other hand, this departure from traditional bearing practice has necessitated extensive research on compatible materials. Ref [48] describes work on advanced ball bearings for the future Space Transportation Main Engines (STME) and the SSME Alternate Turbopump Development (ATD). The lubrication concept relies on sacrificial wear of the bearing cage (bronze-60% Teflon), and its transfer from the rolling elements to the raceway surface.

Roller element bearings can provide some stiffness, through angular contact design, but the bulk of the axial thrust of the pumps and turbines must be hydraulically balanced, either by back-to-back pump arrangements with no feedback, or, as in the SSME turbopumps, by providing hydraulic feedback to some surface acting as the balancing piston [40]. Future designs are likely to feature hydrostatic bearings, which rely on a very thin fluid film to support the rotor without solid contact with the casing. The advantages of these bearings are summarized in Table 1 from Ref [40]. The most important are the removal of the surface speed limitation of ball bearings and the much higher radial stiffness. The surface speed is expressed by the “DN product” in conventional bearings, and, as Table 2 indicates, is in the range of $1-2\times10^6$ (mm) $\times$ (Rpm). This limitation forces the designer to seek bearing locations with the smallest possible diameter, such as outboard of the pumps and turbines, but these bearing locations tend to lower the 1st natural frequency, and to interfere with flow approach to the pumps.

Item	Hydrostatic bearing	Ball bearing
Speed limit	None	2.0M DN LH_2 1.75M DN LO_2
Life limit	Unlimited steady state Transient rub concern	= 2h
Design constraints	Supply pressure availability	Shaft diameter for torque transmission
Direct stiffness	1 to >5M lb/in.	0.5 to 1M lb/in. for duplex pair
Damping	50 to >500 $\frac{\text{lb/s}}{\text{in.}}$	2 to 5 $\frac{\text{lb/s}}{\text{in.}}$
Rotor-dynamics	No constraints for optimum position Adjustable stiffness and damping	Position constraints No adjustable damping

Table 1. Hydrostatic bearing benefits

As in all turbo machines, seals are required to reduce or prevent leakage of fluids around the shaft from high to low pressure areas. The high linear speeds of the rocket turbopump surfaces, as well as, in some cases, the oxidizing nature of the fluid, dictates the use of non-contact type seals, which, by their nature, allow a nonzero leakage rate. Thus, in oxidizer turbopump with the fuel-rich turbine on same shaft, there is a need to introduce some high-pressure inert gas into a region separating the two fluids, with seals provided to minimize leakage (and hence inventory) of this purge gas. Multi-tooth labyrinth seals are standard in jet engines, and were incorporated at various points in the original SSME turbo pumps. However, after a sequence of redesigns to correct vibration problems most of these have been replaced by very low clearance smooth cylindrical seals, which have much higher radial stiffness and significantly contribute to raising the lowest natural frequencies of the rotor (in fact, these seals can be viewed as a transition to hydrostatic bearing designs).

TABLE 2 - Summary of Current Turbopump Bearing Capabilities

Bearing DN X 10^{-6} (mm x RPM)	Bearing type	Bore, mm	Materials			Load, lb_r		Speed 10^3 rpm	Coolant		Experience		Maximum test hours per bearing (no failure)	Maximum temperature °F
			Ball or roller	Races	Cage	Axial	Radial		Fluid	Flowrate, gpm	Turbopump	Test rig		
1.4	Ball	35	Halmo	Halmo	S-Monel	1,400	1350	40	RP-1	0.2	X		5	800
0.476	Ball	70	52100	52100	AMS 4616	5,900	4700	6.8	RP-1	0.1	X		1.75	250
0.715	Tandem Ball	130	52100	52100	AMS 4616	55,000	0	5.5	RP-1	4.0	X		20	350
1.4	Roller	35	4620	4620	AMS 4616	0	3700	40.0	RP-1	0.2	X		5	350
0.476	Roller	70	52100	52100	AMS 4616	0	4000	6.8	RP-1	0.1	X		1.75	250
0.935	Roller	170	11	11	AMS 4616	0	500	5.5	RP-1	1	X		100	800
1.6	Ball	40	K5H[1]	440-C	25% GFT[2]	2,700	NA	40	50-50[3]	14		X	0.2	NA
1.13	Ball	45	K.96[4]	K.96	Graphite[12]	300	0	25	50-50	1.1		X	0.6	NA
1.6	Roller	40	440-C	440-C	25% GFT[2]	0	500	40	50-50	8 to 10		X	0.2	NA
1.13	Ball	45	440-C	440-C	Armalon	330	0	25	EDA[5]	1.5		X	1	NA
1.13	Ball	45	440-C	440-C	Armalon	315	0	25	B_5H_9[6]	1		X	0.4	NA
1.27	Ball	45	440-C	440-C	Armalon	800	100	28.3	Liquid hydrogen	100	X		6	-350
1.55	Ball	45	440-C	440-C	Armalon	300	0	34.5	Liquid hydrogen	10		X	9	NA
1.2	Ball	50	440-C	440-C	Armalon	3,000	NA	24	Liquid hydrogen	20	X		3	NA
1.7	Ball	60	440-C	440-C	Armalon	800	100	28.3	Liquid hydrogen	20	X		6	-350
2.05	Ball	65	440-C	440-C	Armalon	2,200	100	31.5	Liquid hydrogen	40	X		3	-350
1.46	3TandemBall	110	440-C	440-C	Armalon	36,000	NA	13.3	Liquid hydrogen	150		X	0.75	NA
3.0	Ball	150	440-C	440-C	Armalon	1,000	0	20	Liquid hydrogen	150		X	0.5	NA
3.0	Ball	200	440-C	440-C	Armalon	5,000	0	15	Liquid hydrogen	150		X	1.6	NA
1.2	Roller	50	440-C	440-C	Armalon	0	2000	24	Liquid hydrogen	20	X		3	NA
1.6	Roller	120	440-C	440-C	Armalon	0	5000	13.3	Liquid hydrogen	26		X	1.63	NA
1.05	Ball	35	440-C	440-C	Rulon	0 to 400	150	30	Gaseous hydrogen	0.02 to 0.2 lb/sec	X		5.5	-400 TO +60
1.2	Ball	40	440-C	440-C	Rulon	140	200	30	Gaseous hydrogen	0.03 lb/sec	X		5.5	-400 TO +60
1.55	Ball	45	440-C	440-C	Armalon	300	0	34.5	Gaseous hydrogen	0.1 lb/sec		X	9	NA
0.36	Roller	30	440-C	440-C	7	0	300	12	Gaseous hydrogen	NA	X		5.5	-60
0.48	Roller	40	440-C	440-C	7	0	200	12	Gaseous hydrogen	0.02 lb/sec	X		5.5	-60
1.13	Ball	45	440-C	440-C	Armalon	330	0	25	IRFNA[8]	5 gpm		X	1	NA
1.6	Ball	40	440-C	440-C	25% GFT	1,500	NA	40	N_2O_4	5 to 15		X	0.25	NA
1.13	Ball	45	440-C	440-C	Armalon	330	0	25	N_2O_4	2 to 5		X	1	NA
1.25	Ball	50	K5H	440-C	25% GFT	2,500	NA	25	N_2O_4	5 to 15		X	0.25	NA
1.6	Roller	40	440-C	440-C	25% GFT	0	1000	40	N_2O_4	5 to 15		X	0.25	NA
1.13	Ball	45	440-C	440-C	Armalon	500	0	25	Liquid oxygen	5		X	15	-250
0.53	Ball	60	440-C	440-C	Armalon	3,500	0	8.8	Liquid oxygen	10	X		6	-250
0.44	Ball	110	440-C	440-C	Armalon	18,000	NA	4	Liquid oxygen	8.5		X	0.9	NA
0.42	Roller	105	440-C	440-C	Armalon	0	3750	4	Liquid oxygen	2		X	2	NA
0.16	Ball	45	440-C	440-C	K-Monel	400	0	3.6	Liquid fluorine	Submerged		X	1	NA
0.16	Ball	45	K162B[9]	440-C	K-Monel	400	0	3.6	Liquid fluorine	Submerged		X	1	NA
1.0	Ball	50	440-C	440-C	BN44010	400 to 12	0	20	Liquid fluorine	12 to 20		X	0.5	-293

[1]Tungsten-titanium carbide
[2]Glass-filled teflon
[3]UDMH-N2H4 (50-50 mixture)
[4]Tungsten carbide
[5]Ethylene diamine
[6]Pentaborane
[7]Plated lead on silver on AMS 4616
[8]Inhibited red fuming nitric acid
[9]Titanium carbide
[10]Berylco Nickel 440
[11]Bower 315
[12]U.S.graphite, grade 2