Prediction of Ball and Roller Bearing Thermal and Kinematic Performance by Computer Analysis*

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Bearings act within a load support system in mutual support of a load vector and share in the control of shaft motion. The load system contains (as a minimum) a shaft, housing, and more than one bearing. The system is part of machinery which experiences a thermomechanical dialogue within and across the boundaries of its physical volume. Analysis examines this dialogue and constructs mathematical models. Their complexity requires computerization. This results in software which then enables a design methodology emphasizing numerical exploration of a competitive variety of load support system concepts, prior to hardware commitment.

Rotating load support has received parallel attention with the evolution in the sophistication of machinery. Prior to constraints on mass content and in the presence of loads, speeds, and temperatures which were moderate for rolling element bearing materials, little need was seen for detailed analysis of the component. There was even less motivation to understand the surrounding interactions. Large margins available in the reserves of bearing material properties allowed escape from the penalties for the severe approximations in computation techniques. This design efficiency can no longer be afforded as the luxury which it now is recognized to be. Applications, for example, have materialized in which highly loaded precision supports have to survive for short periods, minutes instead of years. Thermomechanical environments have been specified in which only solid-solid lubrication is present. These and other needs have provided motivation for the creation and use of novel materials. Their property definitions and performance in bearings demand new and accurate representation.

The explicit need for design calculation reliability requires a detailed assessment of the role of primary and secondary effects within local control volumes of individual bearing contacts. The cross-coupling interactions of the global thermomechanical environment with its local counterpart require similar detailed understanding. This is fortunately made possible by the evolving body of knowledge concerning concentrated contact micromechanics and by the availability of contemporary high speed digital computers.

The material which follows suggests characteristics of good computerized analysis software. These general remarks and an overview of representative software precede a more detailed discussion of load support system analysis program structure. Particular attention is directed at a recent cylindrical roller bearing analysis as an example of the available design tools. Selected software modules are then examined to reveal the detail inherent in contemporary analysis. This leads to a brief section on current design computation which seeks to suggest when and why computerized analysis is warranted. An example concludes the argument offered for such design methodology. Finally, remarks are made concerning needs for model development to address effects which are now considered to be secondary but are anticipated to emerge to primary status in the near future.

Software Design and Evolution

Preferred Software Design

The past 20 years have witnessed a remarkable increase in the computation power and flexibility available for practical analysis and design. Cumbersome multiple-pass executions with extended user

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participation in the processing steps have given way to interactive communication. Contemporary software for the analysis of load support systems can be constructed as an accurate detailed simulation whose execution teaches a novice, serves a practitioner, and improves by "instruction" from the expert. Good software is made so that it and the user are an evolving symbiotic entity whose ability to assess and create grows with experience. It should be designed so that novice users default into *standard* conditions and obtain knowledge for that realm of operation. For example, all materials have the same standard steel properties. Housings do not deflect; temperatures are standard ambient; full symmetry prevails; a standard lubricant is selected; and so on. Deactivation of any of these defaults by the user parallels the user's developing experience and enables the investigation of the influence of these specific parameters on performance. As examples, rings are allowed to misaline and influence L_{10} life, or oil supply rate is varied to remove heat generated at higher operating speeds.

Finally, experienced users can incorporate their own subroutines or variants. At this stage of participation, the user is an active partner in computerized analysis and design.

Evolution of Contemporary Software

The first use of digital computers for the analysis of bearings can be credited to Jones. He examined a single ball bearing under thrust load (ref. 2). By postulating a hypothesis concerning the kinematic behavior of balls, he formulated a definition of ball motion. The first load support system analysis paper followed shortly thereafter in 1960, again by Jones (ref. 3). Here an elastic shaft was considered mechanically together with ball and/or roller bearings in mutual support of a general load vector. The formulation was reported to be implemented on an IBM 704 computer. Both papers presented the details of mathematical formulation. Software architecture description, discussions of success with the convergence of iterative procedures or computation time experiences, were noticeably absent. Eleven years later, Harris (refs. 4 and 5) extended Jones' single ball bearing analysis by relaxing the restriction of single raceway response to gyroscopic moments. Using digital computers, he then incorporated a description of a Newtonian separating lubricant, which was characterized by a pressure and temperature dependent viscosity (ref. 6) In 1966 Harris (ref. 7) introduced an analysis which considered skidding at high speeds in the presence of a fluid whose viscosity was assumed to be an exponential function of pressure and temperature. But a severe restriction was imposed which insured that all rollers experience the conditions identical to those present at the most heavily loaded one. Each contact was specified to have the same film thickness, rolling speed, etc. Boness (ref. 8) revealed experimental data which contradicted this assumption on roller speeds, and set Poplawski (ref. 9) on an alternative extended formulation of the field equation set. Poplawski included the roller speed about its own center as an independent variable. This kinematic condition allowed for the computation of a speed distribution among rollers and a load distribution of the retainer. Fluid churning and cage pilot surface friction effects were also included. Rumbarger (ref. 10) continued the evolution of high speed roller bearing analysis by relaxing the isothermal elastohydrodynamic (EHD) film requirement and by adding a comprehensive fluid drag formulation. The major contribution of this work was to display the interdisciplinary computerized systems analysis approach necessary to obtain meaningful results.

Major advances in further software generation have taken place within the past few years. Systems analysis has been written which considers the whole spectrum of partial to full EHD formulations for a variety of shaft-mounted bearing types in mutual support of a load vector. Ball, cylindrical, and tapered roller bearings are considered in load-support system software by Crecelius (ref. 11), as well as mechanical assembly programs by Ragen (ref. 12), and Crecelius and Kleckner (ref. 13). These specific formulations consider the systems to reside in, and interact with, a time transient thermal environment. Other programs have been written to treat a single cylindrical (ref. 14) or spherical (ref. 15) rolling-element bearings in a transient thermal environment. Cylindrical bearing isothermal dynamic analysis has been written by Conry (ref. 16), Brown (ref. 17), and Gupta (ref. 18). Ball-bearing dynamics, originally formulated by Walters (ref. 19), were expanded in generality and implemented by Gupta (ref. 20).

Various aspects of the substantial efforts to develop tribological understanding by analysis and experimentation, which led to the development of models and then individual software modules are summarized in discussions by Dowson (ref. 21), McGrew (ref. 22), Cheng (ref. 23), Anderson (ref. 24), Tallian (ref. 25) and Pirvics (ref. 26). Additional commentary of software characteristics as well as selected descriptions have been noted by Gupta (ref. 27) and Sibley (ref. 28).

Software Architecture

Introduction and General Definition

Software is built to automate the sequence of numerical computation steps taken to solve for the unknown values of variables in an equation set. The correctness of the calculated values depends on the validity of the mathematical models and on the processing of the information between steps in the computation sequence. Each module representing the models within the software must present a parallel level of simulation sophistication detail. The least sensitive module contributing to the governing field equation set determines the performance level of the complete program.

Software architecture presents a plan which is sensitive to these elementary but essential concepts. It does so in the form of a master flowchart which itemizes computation needs, displays the logic flow, and defines the solution strategy.

Example

A flowchart which describes the control of 131 modules, represented by approximately 12 000 card images, is shown in figure 1. It represents the architecture for Cybean (cylindrical bearing analysis) (ref. 14). Exchanges of data with the user world, logic flow, and computation sequence are readily seen. For example, the computations performed by modules within box 1 in figure 1 provide roller and ring loads. Figure 2 details a module that computes the force which arises in a rolling element to flange interaction.

Once the field equations are assembled, a ''solver'' module (box 2 in fig. 1) is activated. Derived quantities are then computed (box 3). After output is prepared for the user (box 4) a table of options is checked and program control is appropriately transferred.

Cybean examines a single cylindrical bearing's performance. The architecture for more complex systems software, like Shaberth (ref. 11) and Transim (ref. 12), bears the skyscraper to single family residence analogy. However, the elements of successful software design, with emphasis on balanced sophistication and modularity, are common.

Classification

General software for bearing analysis examines forces and moments in a three dimensional space which are time transient and temperature dependent. A complete mechanical assembly, containing one or more load support systems, is considered. This general software contains, as subsets within its architecture, levels which consider systems of decreasing complexity:

Level	What is simulated	Kinematic representation	Thermal representation
1	Assembly	Dynamic	Time transient thermal
2	Assembly	Quasidynamic	Time transient thermal
3	Component	Dynamic	Time transient thermal
4a	↓	Dynamic	Steady state thermal
4b		Quasidynamic	Time transient thermal
5		Quasidynamic	Steady state thermal
6		Quasidynamic	No thermal analysis
7		Quasistatic	No thermal analysis
8		Static	No thermal analysis

Classification Nomenclature

An *assembly* contains one or more load support systems within the nomenclature used above. A component is a single load support unit which may be a ball, cylindrical, tapered, or spherical rolling element bearing. The assembly can be represented by a lumped mass nodal network. The nodes

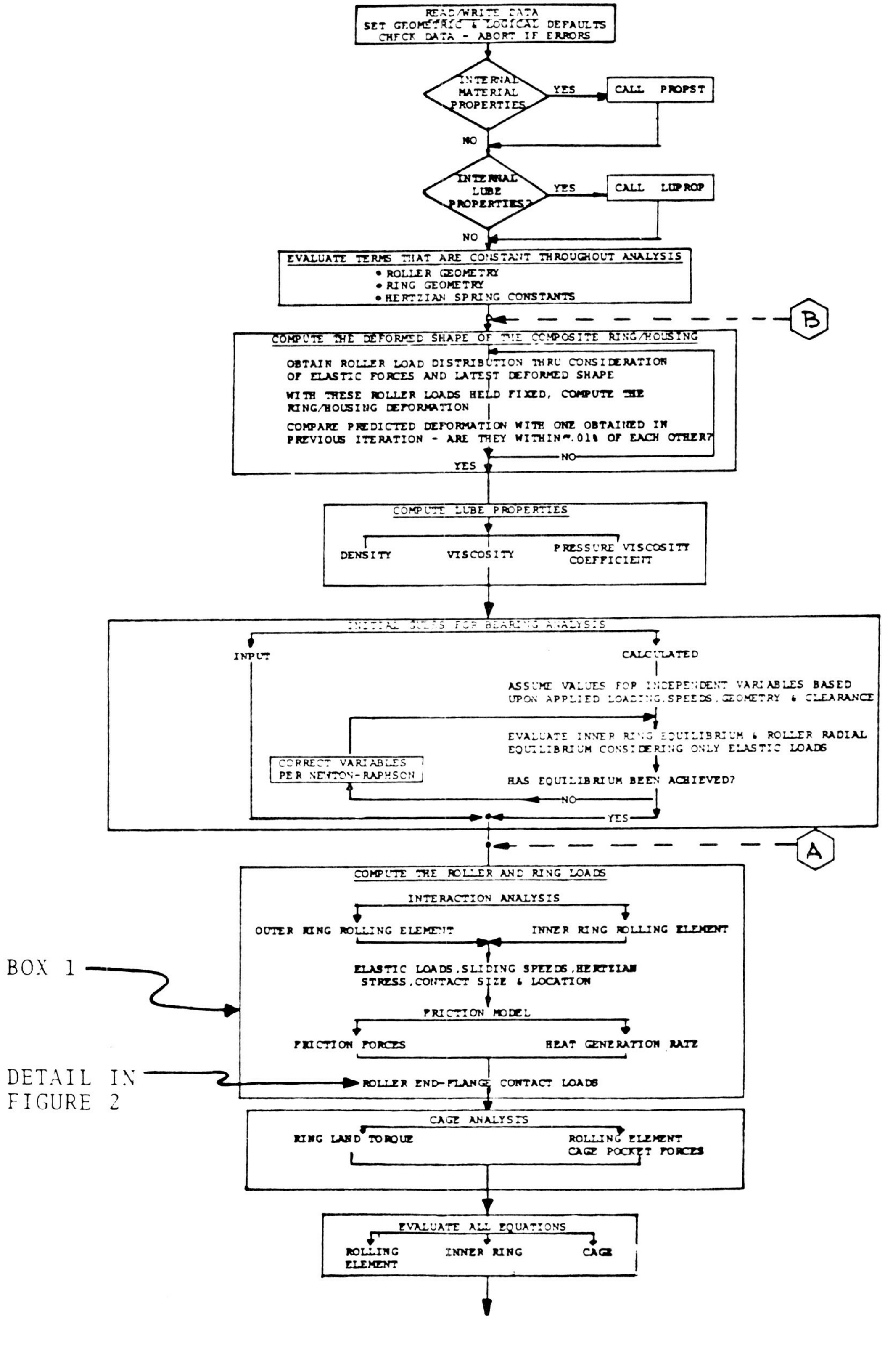

Figure 1. - Cybean flowchart.

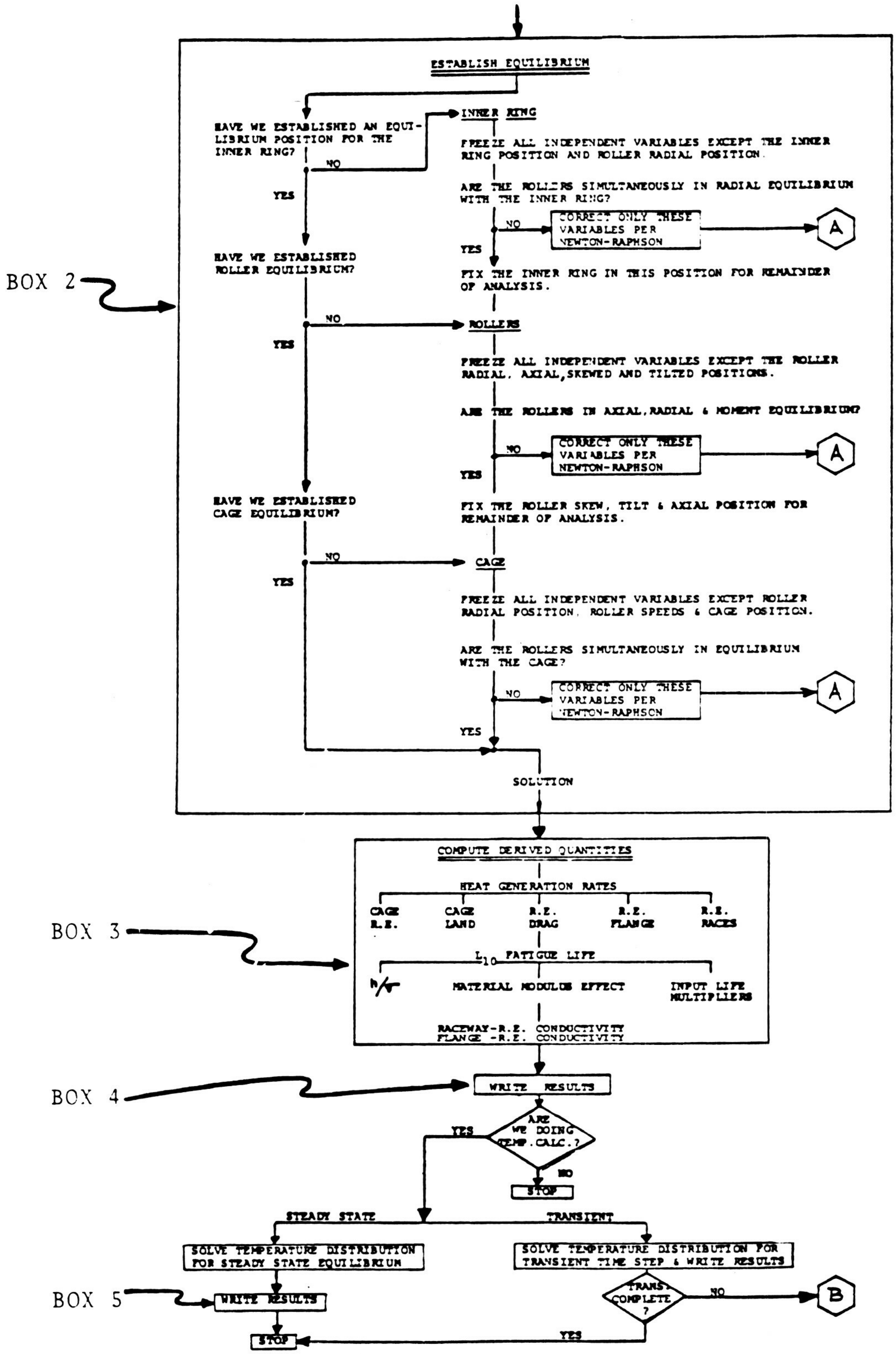

Figure 1. - Concluded. Cybean flowchart.

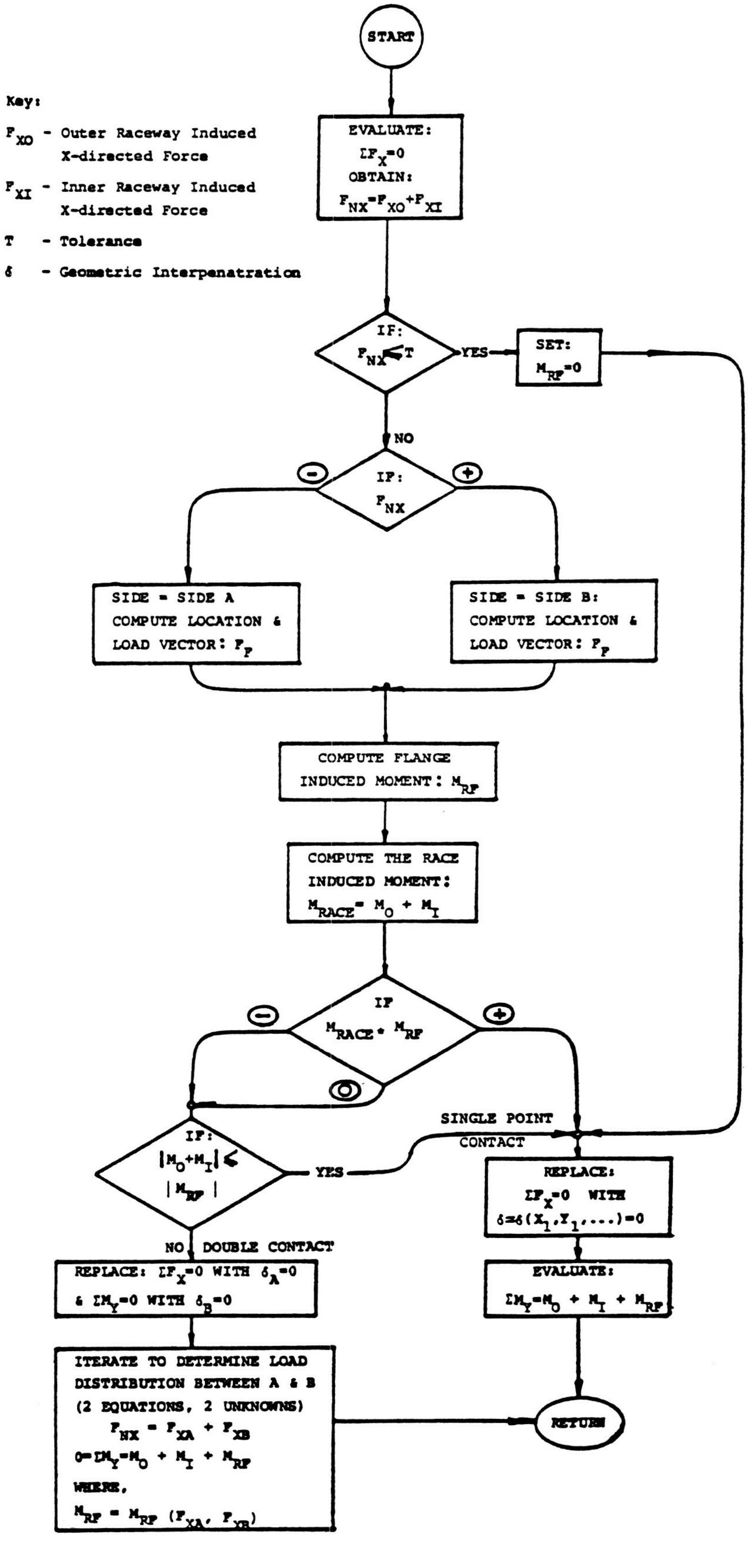

Figure 2. - Solution algorithm for multiple flange contacts.

transfer energy by conduction, convection, and radiation. They represent the mass, surface area, and physical properties of the space they replace. They may be heat sources or sinks. Thus, thermal refers to the software's ability to account for temperature distribution effects on a scale defined by the nodal volumes within the assembly. Time transient thermal capability refers to the updating of the system temperature map to reflect the cross-coupled influence of heat exchange mechanisms and temperature dependent material properties as time progresses. Isothermal refers to the assumption that all locations within the control volume considered are at the same temperature.

Static, quasistatic, quasidynamic and dynamic program designations refer to the degree with which time transient motions of individual elements of a component are detailed.

A fully "dynamic" code defines a field equation set within which force, F_j, and moment, G_j, Newtonian equilibrium is written for each i^{th} element, retainer, raceway and shaft of mass, M_i, and moment of inertia, I_i, in the j^{th} direction:

$$M_i \ddot{\xi}_{ij} = F_j$$

$$I_i \dot{\omega}_{ij} = G_j$$

Three independent variables, ξ, and their derivatives in time, describe the motion of a given i^{th} mass center in an inertial reference frame. Three more variables define rotations about that mass center. Numerical formulation for N rolling elements, two raceways and a retainer require a field equation set of magnitude $[6(N+1)+1]$. A typical 30-element cylindrical roller bearing dynamic description requires the integration of 187 simultaneous nonlinear equations for each time step.

The opposite extreme for the characterization of time transient motion is to specify its absence, and equate F_j and G_j to zero. This gives rise to level 8, "static" formulations. Here, Hertzian pressure distributions in contacts are assumed to govern the interactions between elements and rings due to an applied force vector. No account is taken of traction or those forces created by centrifugal and gyroscopic effects. The individual motion of elements within the component is not recognized.

The departure from this elementary viewpoint begins with the recognition that load distribution, at higher speeds, is altered by centrifugal loads. Recognition of speed begins with examination of spin as well as roll components in element motion. Initially, Coulomb friction was assumed to govern the creation of traction forces, and angular velocities were determined by "raceway control" (ref. 2). The latter specified that a ball would experience pure rolling on the controlling raceway and spin with respect to the other. This restriction was progressively relaxed (ref. 4) as Coulomb friction gave way to the traction simulation generality afforded by the consideration of fluid film separation in the contact conjunctions. The implementation of these considerations of motion in ball and roller bearing programs, the departure from epicyclic constraints, the formulation to account for velocity vector variation in the rolling element set classifies level 7, "quasistatic" software.

The admission of circumferential inertial terms into that equilibrium set leads to the definition of "quasidynamic" software resident in level 2 as well as levels 4b to 6. Specifically, individual element angular velocities $\omega_{\theta i}$ are computed together with element positions in the retainer. With $\omega_{\theta i}$ and its position known for each i^{th} element, the circumferential inertial term is accounted for in a particular equilibrium state in time (ref. 11) by evaluating $F_{\theta i}$ as

$$F_{\theta i} = M_i \dot{\omega}_{\theta i} = M_i \frac{\partial \omega_{\theta i}}{\partial t} = M_i \omega_{\theta i} \frac{\partial \omega_{\theta i}}{\partial \theta}$$

The partial derivative $\partial \omega_{\theta i} / \partial \theta$ is evaluated from numerical differences of $\omega_{\theta i}$ in the θ direction.

Discussion

The transition from static to dynamic programs recognizes the significance of individual component velocity and acceleration vectors. It also notes that increasingly detailed individual stress distributions are needed within the multiple contact conjunctions for any given element in the formulation of accurate force and moment equilibrium. The sensitivity of the element kinematics to traction coefficient values and, in turn, the sensitivity of the latter to sliding speed, temperature, and EHD film thickness creates mathematical convergence difficulties for solution procedures. It also highlights the requirement for comprehensive level 1 software for a truly detailed representation.

The eight program categories classified in the preceding paragraphs require additional comments concerning availability. Level 1 does not exist, but its assembly is possible. Level 2 is represented by Shaberth (ref. 11) and Transim (ref. 12). Level 3 does not exist but can be conceived as the sequential execution of programs in level 4. Level 4a contains DREB (refs. 18 and 20) and software by Brown (ref. 17) and Conry (ref. 16). Level 4b has Cybean (ref. 14) and Spherbean (ref. 51). The remaining levels contain subsets of the noted programs, specialty software for rougher approximation, and historical programs. The programs noted do not exhaust those available, but are representative of the current state-of-the-art.

Software Modules

Background

Load support assembly analysis starts with the definition of work and heat flux across the global boundaries of the control volume drawn to contain it. The boundaries displace as load vectors are applied, and heat is driven by temperature differences between contents of the volume and the surrounding environment. The understanding of assembly behavior comes from the description of local thermomechanics and their equilibrium cross-coupling with the global system.

The concept of "local" is understood if the global control volume is examined under ever increased magnification. The assembly enlarges out of the viewing window and a particular load support system appears. The system in figure 3 gives way to an element of a rolling bearing complement, as it in turn recedes as focus is achieved for one of several surface contacts seen in figure 4. Examination of this "local" view reveals a volume in space within which reside as many as three deformable materials with temperature dependent properties and irregular topography. The materials interact with each other in a time dependent search for thermodynamic equilibrium with the surrounding space. Evaluation of the energy exchange, within, as well as across, the boundaries of this small volume scales the thermomechanical effects considered to be "local." The evaluation is provided by local software modules which are assembled and coordinated by the plan resident in the program architecture to simulate the global system.

Modules Found Within LS System Analysis Software

Most basic modules begin with the description of the geometries considered to occupy the control volume. An absolute reference frame is established and moving coordinate frames associated with each moving component of the assembly. Figure 5 gives an example of the geometric relationships involved. A transformation module is constructed to map vectors between any two frames. These modules are standard but particular note has to be made concerning accuracy. Typically, linear distances for geometric description are several orders of magnitude larger than interpenetration magnitudes descriptive of contact deformities. Therefore, differences in distances used to describe material interpenetration and partial derivative numerics have to be treated with respect for the single word precision length of the digital computer used. Modules which are developed on extended single precision hardware take considerably longer to execute and may not be transportable to other main frame environments.

Once initial condition geometries are described, their material characteristics have to be identified. This calls for modules which store data, and which represent the constitutive equations for materials. The viscosity and density of a lubricant, for example, are functions of pressure and temperature. Solid materials are characterized by thermal expansion coefficients as well as elastic constants. Heat transfer coefficients may vary with temperature. Modules of this nature describe the assembly and distinguish it as an identifiable geometric and physical entity.

Further identification is provided by modules defining response to excitation. Shafts deflect, rings misaline, and housings distort within a thermal environment as the applied load is processed through load support components.

The execution of geometry and material characterization modules together with the information from the response modules enables the construction of a series of equalities. These consider the balance of surface and body forces to define Newtonian equilibrium for each element.

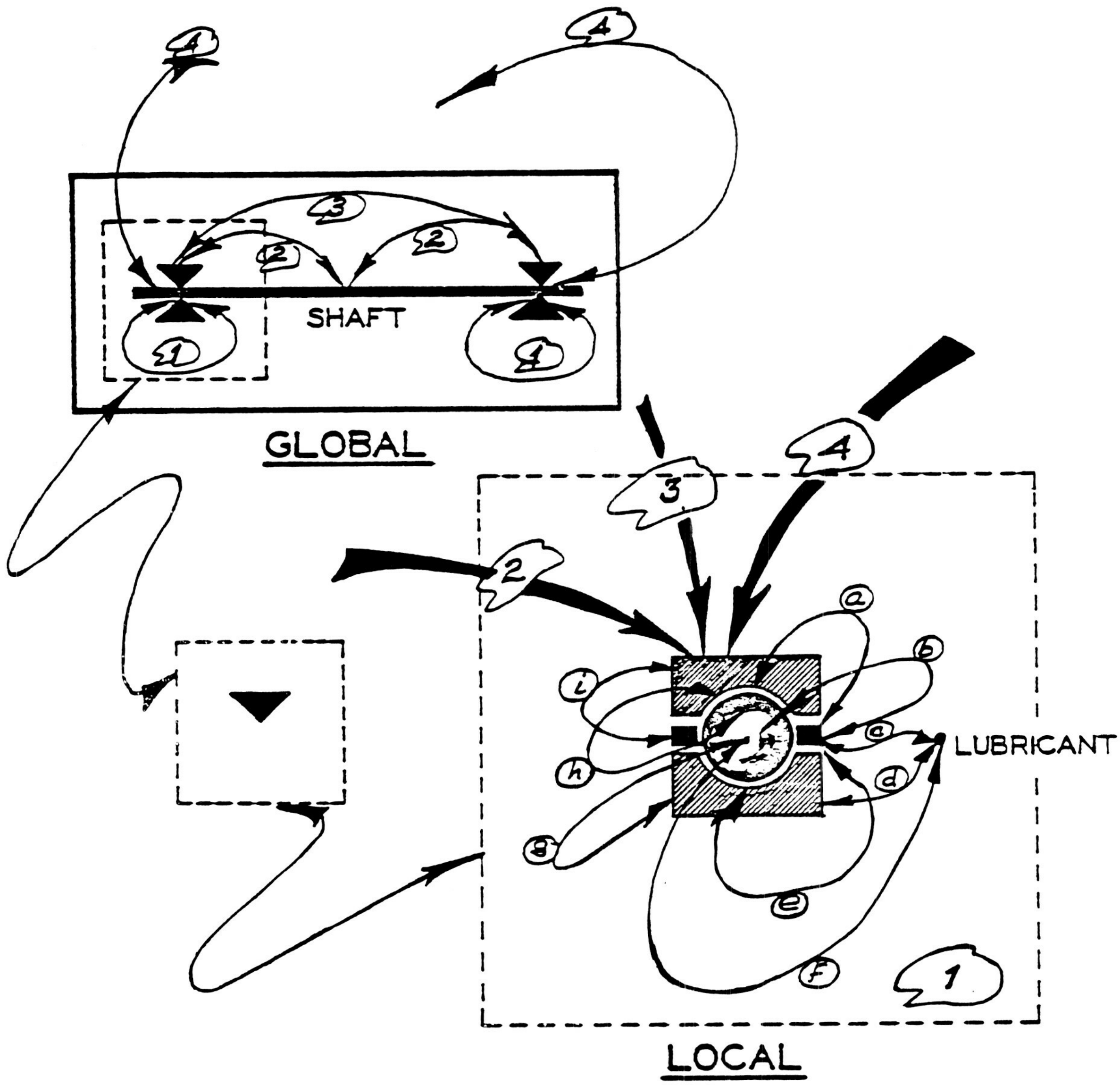

Figure 3. - Load support system thermomechanical dialogue.

Forces can be characterized as those originating from solid-solid and those from solid-fluid interactions. The solid-solid interaction modules start with the definition of a given set of values for the independent position variables which are found for all the load support system components in space. With these positions fixed, the relative positions of the bearing components are examined to determine if their geometries interact or if a free space exists between them. Locations and magnitude of interpenetration are recorded. These values are then used to determine contact stress, contact size, and the integrated force.

The solid-fluid interaction occurs in four ways: raceway/rolling-element traction, flange/rolling element traction, rolling element drag, and cage pocket and land friction. These effects can be computed for the raceway using established contact models (refs. 31 to 35). Flange/rolling element and raceway/rolling element interactions are treated similarly. Rolling element drag is approximated as a function of lubricant properties, speed, and geometry using established equations for external flow. Typical interactions are detailed in work by Kleckner (ref. 14), Ragen (ref. 12), and Gupta (refs. 18 and 20).

The completion of the force equilibrium equations leads to modules whose function is to solve nonlinear field equation sets. Classical Newton-Raphson iterative procedures are conventionally used

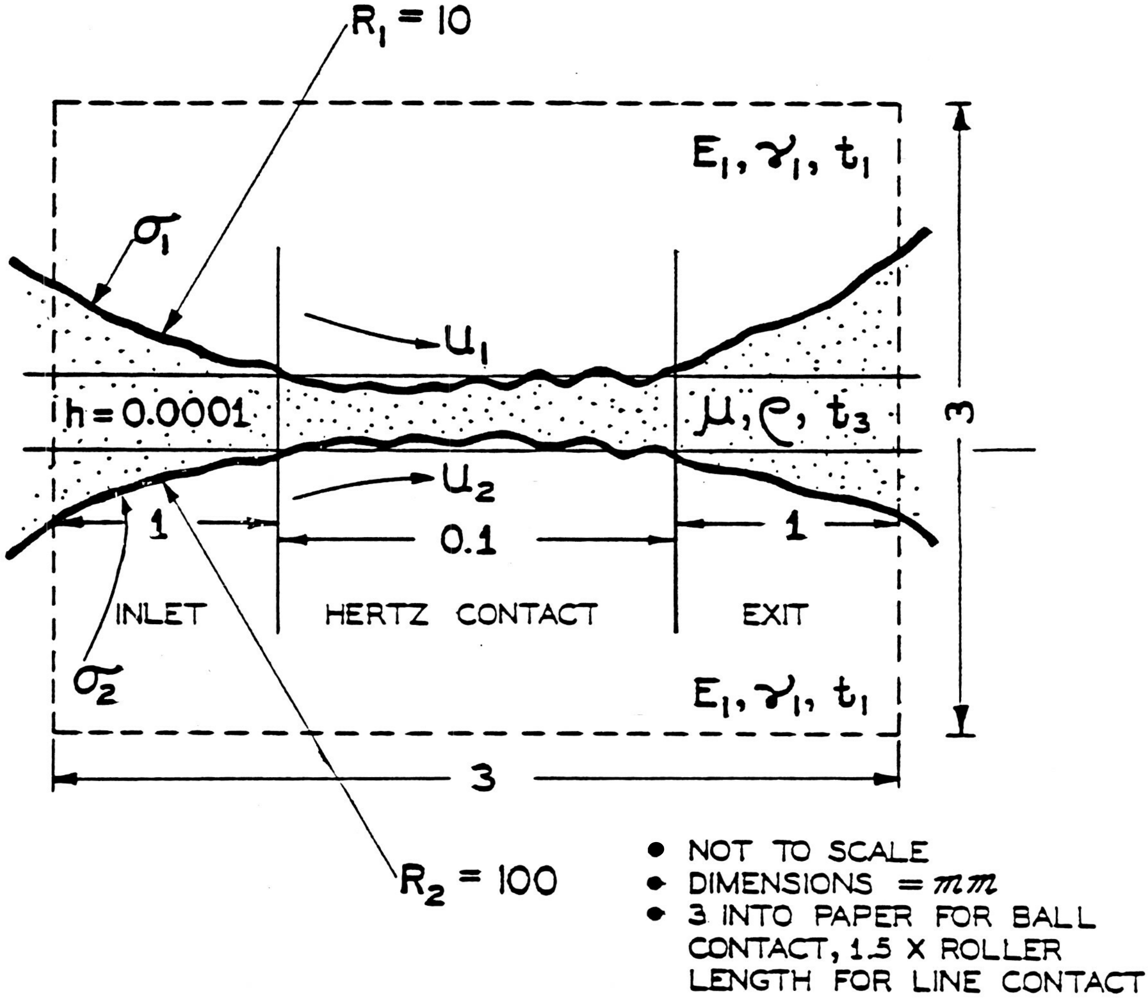

Figure 4. - Local contact control volume.

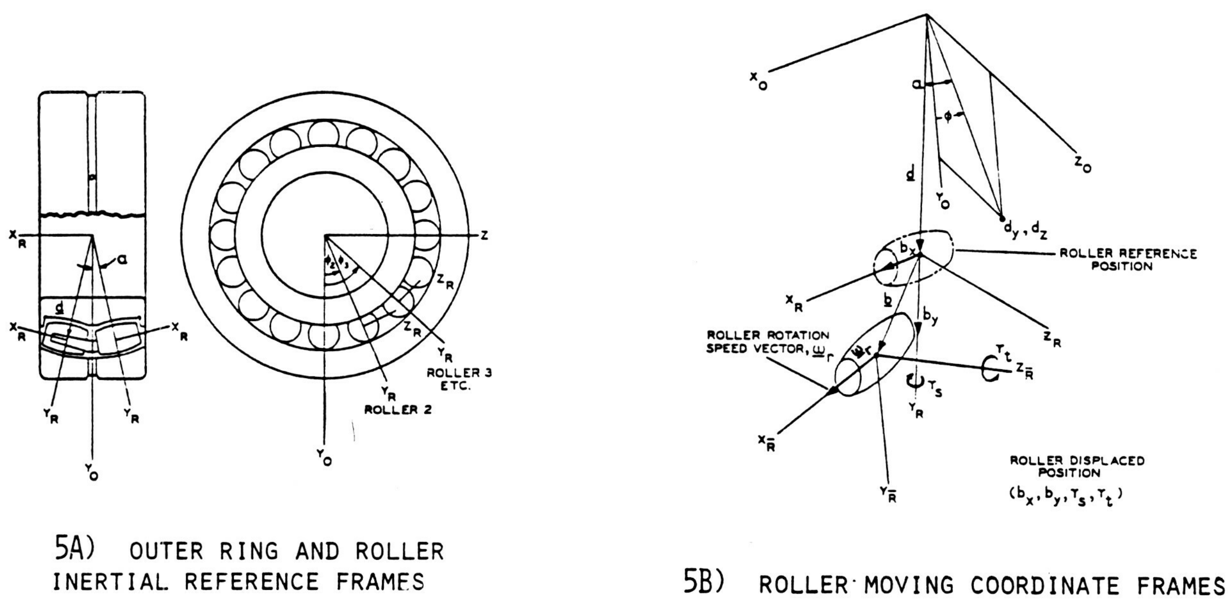

Figure 5. - Spherical roller bearing coordinate frames.

in all but the dynamic formulations. In the latter, Gear's predictor-corrector algorithms (ref. 16), as well as fourth order Runge-Kutta techniques, are used (ref. 18).

Contact Analysis Modules

The "local" nature of contact behavior and its simulation by software modules is at the heart of accurate system representation and deserves additional discussion.

Contact characterization begins by examining the micromechanics of its local control volume (refs. 43 to 47). Relative dimensions of two bodies approaching each other are shown in figure 4. They are characterized by material properties E and ν, and by temperature, t. They are separated from each other by a distance, h, due to the presence of a third medium. The latter has individual temperature and pressure dependent physical properties μ and ρ. The parameter $\Lambda = h/\sigma$, with σ defining surface roughness height, is used to describe the nature of the contact. If $h = 0$, we have dry lubrication in which friction can be represented, to the first order, by a Coulomb relationship. With $\Lambda > 4$, a full separating film exists, preventing the direct solid-solid interaction of asperities. The $0 > \Lambda > 4$ middle ground identifies partial elastohydrodynamic behavior, the practical regime where load is shared by solid-solid as well as solid-fluid interactions. On the local detail level of contact characterization there are no absolute but rather statistical, expectation values for the boundary location of a body. The likelihood that some asperities will interact becomes significant for $\Lambda > 4$.

Software modules which describe the full Λ regime now exist. Most use starvation and thermal adjustment factors to account for inlet heating and quantity of lubrication supply. Cheng (ref. 23), in a recent review paper, summarizes the state-of-the-art in EHD and partial EHD contact formulation. The latter is still under intense investigation.

Contributions to the quantification of surface topography, and micromechanics in the mixed regime, were made by McCool and Gassel (refs. 29 and 30) who recently advanced the ability to simulate the contact of statistically anisotropic rough surfaces.

Methodology for Design with Rolling Element Bearings

Customarily, bearings are incorporated in rotating machinery by selection and not design. Usually a bearing is selected according to load ratings presented in a manufacturer's catalog and sized so that the space left over, after the satisfaction of other requirements, can accommodate it. The manufacturer's load rating is based on work originally performed by Lundberg and Palmgren (refs. 36 and 37). Bearing L_{10} life refers to that load C for which 90% of a group of bearings under identical operating conditions will exhibit one million inner ring revolutions without failure. The formulation of C assumes that failure originates within a subsurface volume which is repeatedly exposed to the stress distributions created by rolling contact. Experimental data were accumulated for bearing steels and led to the standard expression for life L under load P as

$$L_{10} = \left(\frac{C}{P}\right)^K$$

with $K = 3$ or 10/3, depending on the type of bearing. Multiplicative factors can be applied to L to increase the reliability beyond 90%, account for improved quality of modern steel manufacture and the manner in which a separating lubricant film is generated between rolling surfaces (refs. 40 to 42). For example, a 100% reliability can cut 50 000 hours at L_{10} to 2500 at L_0; M-50 steels can raise L_{10} by a factor of 5; and full film separation of rolling surfaces can at least double L_{10} values. The ranges of factor values, the load rating C, and particular geometry for which they hold, appear in manufacturer's catalogs. However, the C values result from simplifications of the basic Lundberg-Palmgren equations and are not directly applicable when bearings experience high speed variations in geometric fit, misalinement, large temperature excursion, inadequate lubrication, flexible supports and multiplane load vectors. Within the AFBMA (Anti Friction Bearing Manufacturers Association) standards leading to catalog ratings, bearing steels are assumed to be clean and to exhibit a minimum of Rockwell C58 hardness. The ratings are based on the additional assumption that radial bearings are loaded so that half of the ball or roller complement carries load, at zero clearance, with rigid rings. Thrust bearings are assumed to distribute load evenly to each element and the axes of inner and outer rings are presumed to be alined.

Contemporary rotating equipment has little respect for these simplifying assumptions. Misalinement of rings by less than 10 minutes in some cylindrical rolling bearings can lead to more than 80 percent decrease in L_{10} life (ref. 38). Changes in shaft mounting fits for tapered roller bearings result in complicated redistribution of radial and axial load (ref. 39).

Typically, a load support assembly is required to restrict shaft deflections to values smaller than a specified maximum over a specified speed and applied load vector range. The required bearing stiffness must be accurately determined by including terms which describe the housing, and shall be such as not to decrease L_{10} life below a specified maximum. The assembly shall fit within a defined space envelope which contains no more than an upper mass limit. The same envelope shall be subject to a temperature gradient which distorts the manufactured geometry. Further requirements may be placed on efficiency and noise generation.

The information needed to calculate these performance variable values is not provided in manufacturer's catalogs. Efforts to bypass the requirement for computerized analysis, by rules of thumb which restrict C/P values to those above 3, 4, or 5, are satisfactory only under conditions where enough equipment has functioned successfully so that the "safety margin" has proven to be adequate. Design by safety margins is a technical and economic luxury which is found to be increasingly unavailable as developing technology makes demands on materials which exhaust their performance capabilities.

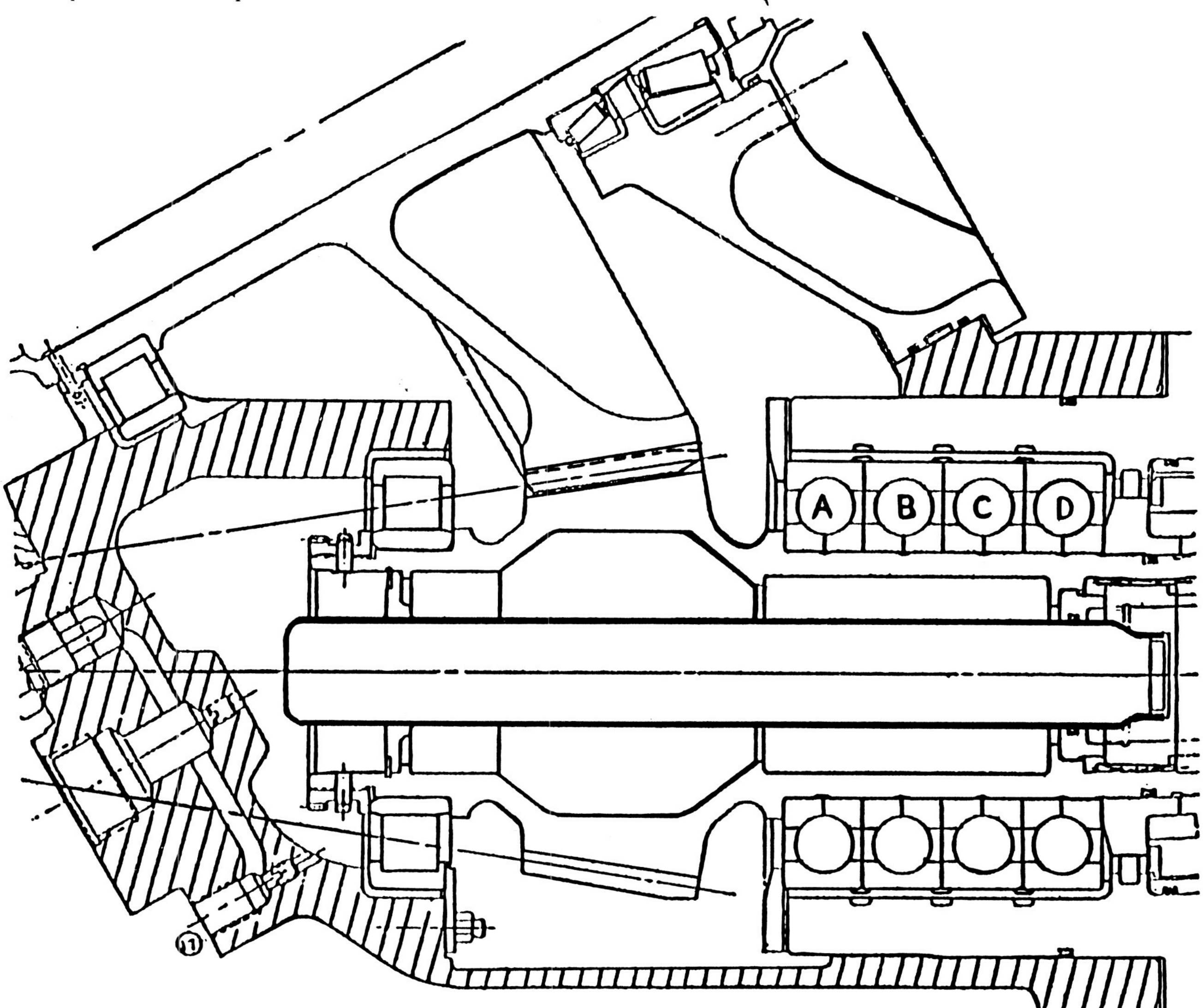

Figure 6. - High speed input pinion (from ref. 25).

The need for computerization of systems analysis results from the complex and interdisciplinary nature of modeling formulations. The nonlinear field equation sets simulating the thermomechanical dialogue are large. If we consider one 30-element cylindrical roller bearing under quasidynamic conditions, 185 variables are needed to describe element and ring positions. The full dynamic representation requires approximately the same. A typical input pinion load support system may contain a cylindrical and two angular contact bearings, a flexible shaft and a temperature field. Very quickly 600 simultaneous equation sets appear for the quasidynamic formulation. Their solution is clearly not possible without the use of numerical methods and high speed digital computers. It also indicates that the expertise required to do so is of a specialized nature.

A specific example of a fully activated level 2 program execution has been reported in detail by Pirvics (ref. 26) for the physical configuration in figure 6. The application is a 13 000-rpm helicopter gearbox input pinion, delivering 1089 kW of power. The system consists of an 80-mm shaft with an integral pinion gear supported between a 16-element cylindrical roller bearing and a stack of four, 15-element ball bearings. Three of the latter are in tandem, one is opposed. The lumped mass equivalent network is seen in figure 7; the lubricant model network in figure 8. A table of computed

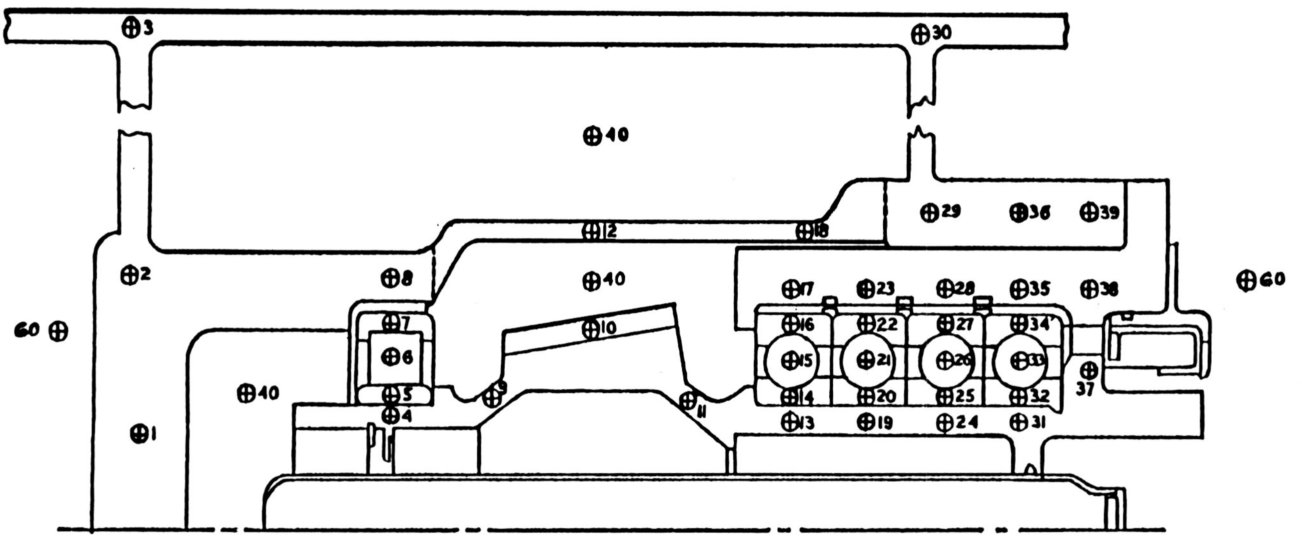

Figure 7. - Lumped mass nodal network (from ref. 25).

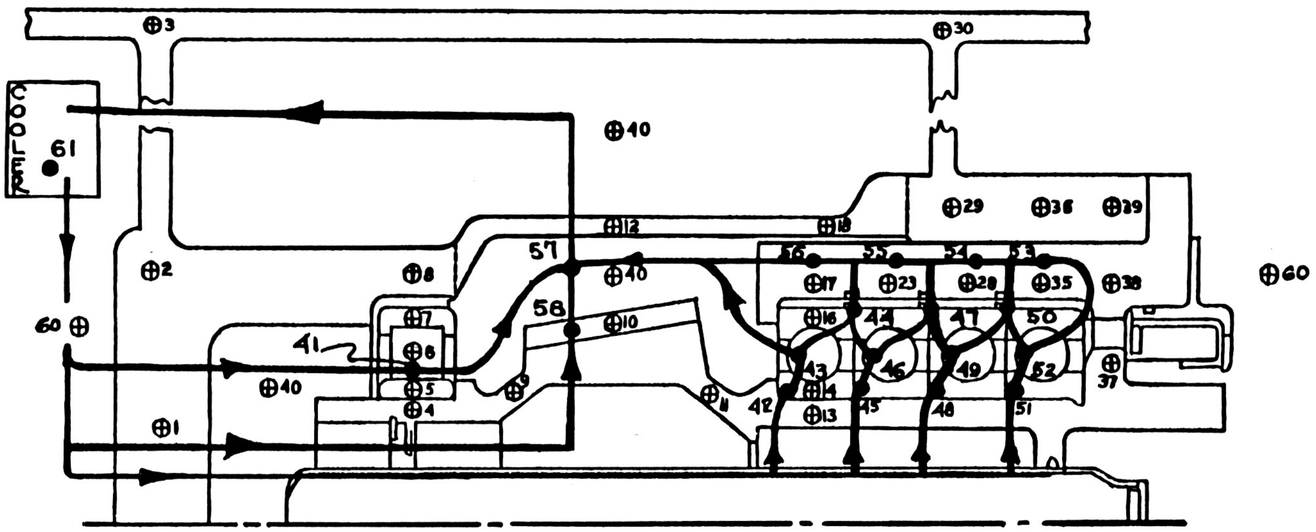

Figure 8. - Lubricant nodal network.

NODE	TEMPERATURE	NODE	TEMPERATURE	NODE	TEMPERATURE	NODE	TEMPERATURE	NODE	TEMPERATURE
1	95	2	97	3	81	4	104	5	104(122)
6	111	7	110(106)	8	105	9	103(89)	10	106
11	95(65)	12	101	13	79	14	83	15	91
16	89(92)	17	99	18	90	19	79	20	84(96)
21	97	22	91(93)	23	90	24	79	25	84(62)
26	97	27	91(90)	28	90	29	88	30	80
31	81	32	86	33	97	34	91(87)	35	89
36	87	37	102	38	86	39	86	40	92
43	100	42	72	43	83	44	94	45	72
46	86	47	97	48	72	49	86	50	97
51	73	52	87	53	97	54	97	55	97
56	96	57	102	58	88				

KNOWN BOUNDARY TEMPERATURES

NODE	TEMPERATURE	NODE	TEMPERATURE	NODE	TEMPERATURE
59	75	60	24	61	70

Figure 9. - Global temperature map calculated temperatures (measured temperatures).

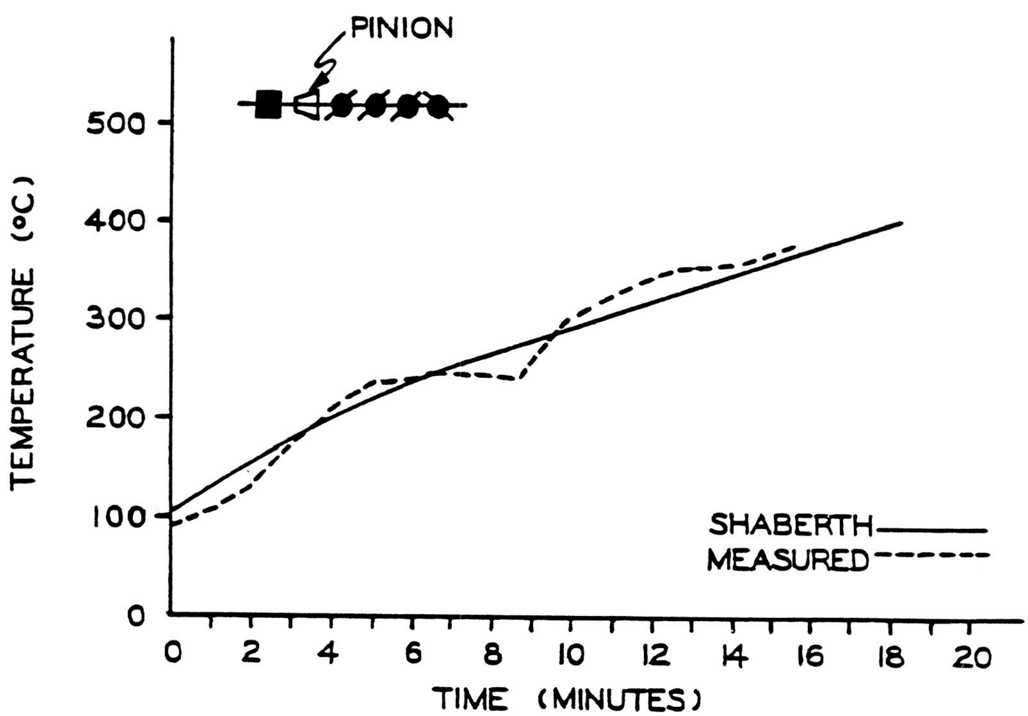

Figure 10. - Pinion shank temperature versus time (from ref. 25).

and measured temperatures and a graph of a time transient computation are in figures 9 and 10. The objective for the analysis was to produce the location and time required to reach an operating temperature of 500° C following lubricant shutoff. The 16-minute computerized projection correlates well with the experimentally observed 16.5 minutes.

Individual ball and cylindrical rolling element bearing dynamic performance simulation results appear in work by Gupta (refs. 48 and 49). Quasidynamic results for a single spherical bearing analysis can be found in reference 15. A system analysis approach for the design of a high speed input pinion is reported by Gassel (ref. 39). The significance of systems analysis may also be seen in the assessment of thermal effects in the early work by Rumbarger (ref. 10). More current discussions are presented by Thompson (ref. 50).

The methodology advocated for load support design is as simple as the message contained in the following statements. Contemporary design is based on interdisciplinary analysis of system performance. System performance is characterized by complex cross-coupling of many variables. Their evaluation requires computerized system simulation of hardware. Simple computer programs give simplistic answers. Sophisticated software is useful only when crediblity is established by corroboration with experiment. Such programs exist and should be used before any material is cut.

Summary Remarks

The preceding material represents an effort to review the existing need and tools present for analytic computerized design of load support systems. It advocates system as opposed to component design. In doing so, it illustrates the peculiar nature of design where concentrated contacts are involved. The point is made, that the concentrated contact *local* thermomechanical event cannot be ignored in the *global* system assessment. This is so because *local* performance failure very quickly cascades to *global* system destruction. The cross-coupled sensitivity of local and global events demands understanding prior to hardware commitment. Such understanding is noted to be available in a variety of programs. The use of software, however, requires an intelligent selection and assurance that results computed are meaningful. Therefore, notes are made concerning good software design, its architecture, and particular modular content.

The basic message is simple. Responsible state-of-the-art design of new, high technology, prototypes which employ rotating supports proceeds at risk without computerized systems analysis. Tools are there to be used. More are evolving with ever increased sophistication and corroboration with actual hardware performance.

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