An Integrated Workflow for Addressing Performance, Dynamics/NVH and Tribological Issues in Scroll Compressors

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ABSTRACT

Durability, NVH, sealing and tribological (friction, wear) aspects of scroll compressor design have been receiving increased attention during development, owing to their growing prevalence in some residential, commercial and automotive HVAC applications. These have been historically addressed either by testing, or more recently, through multi-dimensional CAE (3D FEA and CFD). Both approaches are time-consuming and expensive. As typically applied, detailed 3D analyses are one-off, performed “manually”, involve multiple CAE tools and models used by various experts. Their use in a design optimization process is cumbersome. This paper presents a more practical and automated workflow that integrates such detailed analyses with performance simulation of scroll compressors within a single CAE tool. The methodology combines a flexible-body, multi-body dynamic analysis of moving parts of the scroll compressor, including details of contacts and sealing, along with models of oil film hydrodynamics of journal and thrust bearings, with an established and proven thermodynamic simulation of the gas compression process using fast 1D-flow techniques. The workflow is significantly faster than that of the existing methods, is much richer in the breadth of its predictions, and at the same time its automated nature means fewer manual steps and reduced requirement for expertise. The paper describes the methodology used in the workflow and presents an array of predictions.

1. INTRODUCTION

Scroll compressors have become prevalent in several HVAC applications including residential and commercial heating/cooling, automotive, and refrigeration. This is due to their good volumetric efficiencies, low noise, compactness, higher reliability due to fewer moving parts, mostly oil-free (which avoids contamination) and typically valveless designs. At the same time, with the advent of electrified mobility, thermal management and HVAC have taken a central role in overall energy management and human comfort in vehicle engineering. Optimal design for thermal management in electrified vehicles is a complex endeavor since these systems encompass heating and cooling for passenger comfort, and at the same time temperature control of batteries, electric machines and power electronics during operation. In parallel, global warming concerns are driving the need for efficiency improvements in building heating/cooling, and optimally energy efficient designs. The demand for higher efficiencies mandated by government regulations is also driving the push for new, safer, and low Global Warming Potential (GWP) refrigerants, and transient smart controls for optimal operation. Further, the increased demand for cooling and heating capacity requires scroll compressors to operate and remain durable at higher speeds and pressures. All these motivations are in turn accelerating the use of simulation, virtual prototyping, and digital twins to enable faster times to market and reduced testing costs.

2. KEY PHYSICS OF SCROLL COMPRESSOR AND CAE CHALLENGES

Like all similar machinery, scroll compressor engineering relies on ensuring subsystems involving multiple physical domains operate in unison to achieve certain design objectives, namely efficient pumping with minimal flow (leakage) and friction (bearing) losses, structural and thermal integrity, low levels of noise and wear. Historically, a combination of simplified analyses and testing have been used to this end. However, today’s engineering best practices require that the primary subsystems be subjected to rigorous CAE analyses and simulations to predict and optimize their behavior under specific operating (speed, load) conditions. To address this need, a common workflow is to use CFD and FEA, supplemented by multi-body-dynamics software, along with dedicated in-house design and bearing fluid-film analysis tools. These workflows, which rely on disparate tools, pose multiple challenges:

Incomplete Physics. The entire array of tools required to address all the physics is not available at every organization, or some analyses may have simplifying assumptions (e.g. components always rigid, contacts always dry, no contamination of lubricating oil by refrigerant, etc.).

Inadequate integration of physics. Scroll compressor operation is highly transient and much of the phenomenology is inter-dependent. For example, pressure loads cause scroll deformations which impact sealing (and therefore compression efficiency), bearing friction and wear, which in turn may affect pressures and temperatures. Typical analysis workflows do not account for all these interactions.

Workflow management. Putting together workflows that account even some of these interactions using multiple tools, becomes a software engineering exercise, requiring additional scripts, mediation of data formats and iterative processing. The resulting workflows are typically unwieldy and difficult to maintain as commercial tools evolve.

Lack of flexible fidelity levels. Engineers are often limited to the single fidelity level of the tool that is available, which may be inadequate or, at the other extreme, could be excessive. A process limited to the exclusive use of 3D CFD for flow calculations or for bearing fluid film analyses in scroll compressors is a good example.

As implied by the above, effective use and maintenance of such workflows often require several experts. Even more importantly, they do not lend themselves to optimization and design of experiments (DOE) exercises, typically due to slow model performance (long CPU times, lasting days or more, in some cases). As a result, they are becoming less suitable for today's accelerated product design cycles.

3. AN INTEGRATED APPROACH

The approach described herein is based on a single multi-physics tool which allows modeling of all physical domains (flow, thermal, mechanics, electrical, chemistry etc.), along with interactions between them, using cross-domain elements, under transient conditions. The tool was designed to mitigate the limitations of workflows based on disparate software and co-simulation, described above. It features a single look-and-feel and architecture for all physical domains and cross-domain elements to achieve seamless multi-physics integration. It provides for multiple levels of fidelity in each physical domain (e.g. map-based vs. detailed transient modeling of a compressor, rigid vs. elastic components, dry vs. lubricated contacts, simplified or detailed lubricant properties, etc.). It also allows the entire assembly of multi-physics submodels to be subject to a control system, also integrated into the overall model. Finally, it provides a comprehensive set of distributed (parallel) processing, automation, optimization, and DOE features.

While seamless integration is quite often the right (even the required) way, e.g. when modeling the interaction elastic deformations and bearing oil films, in some cases the coupling between physics is weaker, or one-way, offering opportunities for faster solutions. The approach also provides "no-hands" automation features, which in such situations, break the process into multiple simulations and replace seamless *integration* by seamless *data transfer*.

The scroll compressor multi-physics workflow effectively combines 0D and 1D solutions for compressor thermodynamic and flow modeling, with 3D multi-body dynamics (MBD) of moving parts of the compressor. The moving parts of the compressor can each be modeled as rigid, or flexible, depending on the need. Tribological models of contacts, journal and thrust bearings, in which details of lubricant properties are also considered, can be seamlessly coupled to the MBD model. Loads on the structural parts of the compressor (i.e. housing) can also be used to predict housing vibrations and noise. The following sections describe the physical elements of the approach and workflow.

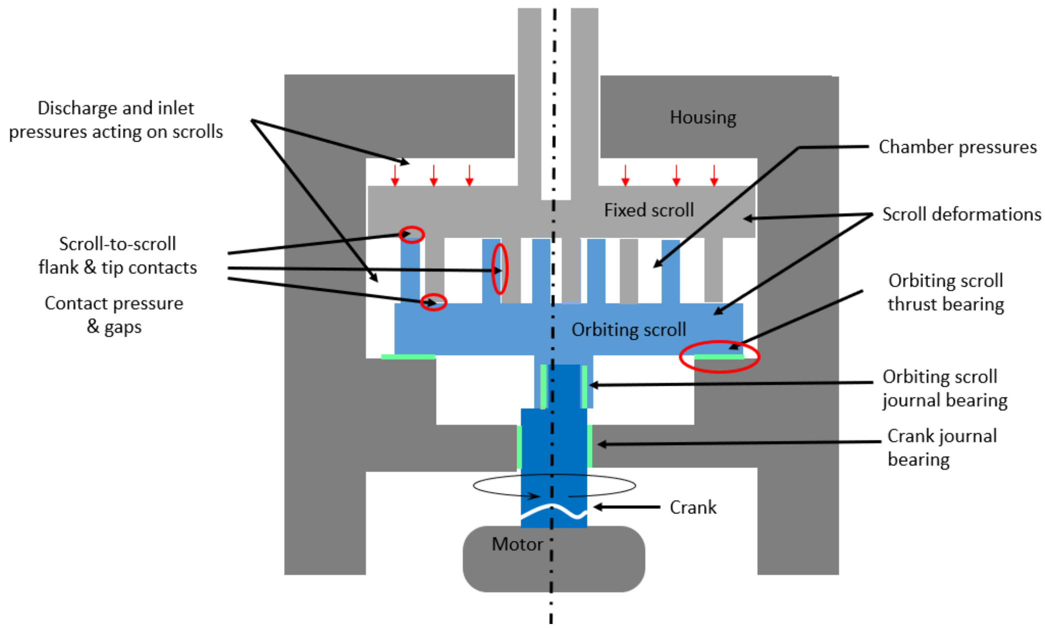

Figure 1: Schematic rendering of scroll compressor performance phenomenology considered (details of couplings preventing rotation of scrolls not shown)

4. ELEMENTS OF THE WORKFLOW

4.1 Fluid flow and Thermodynamics of compression

The thermodynamics and flow of gas intake, compression and discharge, i.e. core "performance" aspects of the compressor, are typically simulated using the 1D thermo-fluid elements of the software, that model transient flow in compressor chambers, suction and discharge ports, the action of suction and discharge (e.g. reed) valves, as well as the system of which the compressor is only one part. The methodology is applicable to various pump and compressor types (vane, gear and gerotor pumps, reciprocating, screw or scroll compressors). For each of these applications, it features a capability for automatic creation of a complete, ready-to-run submodel of compression thermodynamics, starting with a CAD (3D Solid) model of the geometry (vane, gear, gerotor, and scroll). For scroll compressors this involves automatic generation of the chamber "wetted" areas and volumes tables as a function of the scroll crank angle and embedding the information into the submodel.

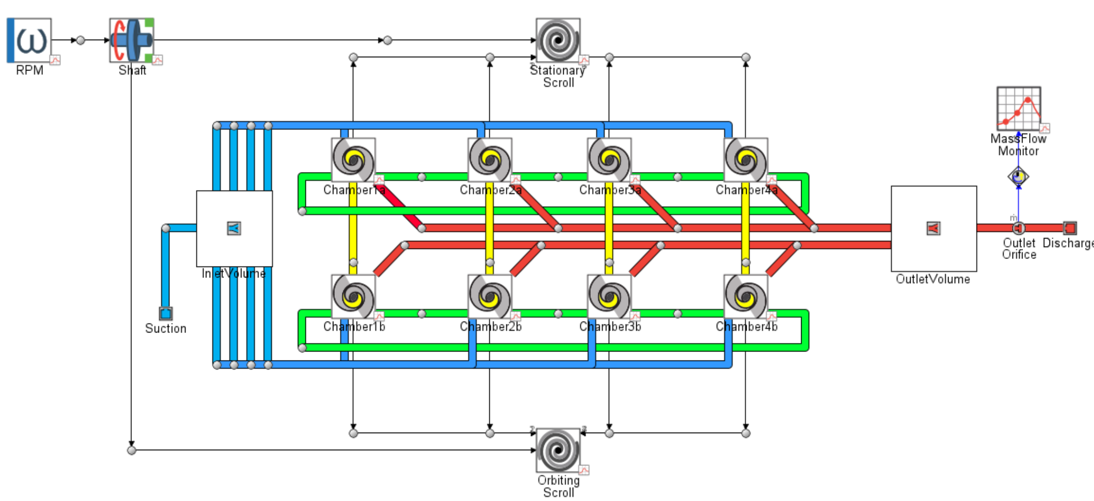

Figure 2: An automatically generated submodel of an 8-chamber scroll compressor performance

Figure. 2 shows a scroll compressor model where the blue lines represent the suction paths into the chambers, red lines represent the discharge paths, green lines represent the internal leakage through the flank clearance, and yellow lines represents the communication between the fixed and orbiting chambers when they are open to each other during the last revolution of the compression cycle. As for the internal leakage modeling, two major terms, the flank and radial leakages, can be added to the model. In this study, the flank clearance is an input to the model but for simplicity, the radial leakage was not modeled. The tool allows an easy drop-in study of different types of refrigerants, and it uses NIST REFPROP for obtaining the fluid properties which can be in any state (i.e., gas, liquid, two-phase, or supercritical region).
Elements of the methodology pertinent to scroll compressor thermodynamic performance, and their successful use for compressor design improvement or optimization have been described in (D'Amico et al., 2022), (Ziolkowski, 2022) (Ziolkowski, 2020), (Fischer, 2019), (Harrison et al., 2018) and (Pham & Lehocky, 2016). Through these and other applications, the use of the 0D/1D approach has been shown to be an effective level of fidelity (vs. CFD) for product design and refinement.

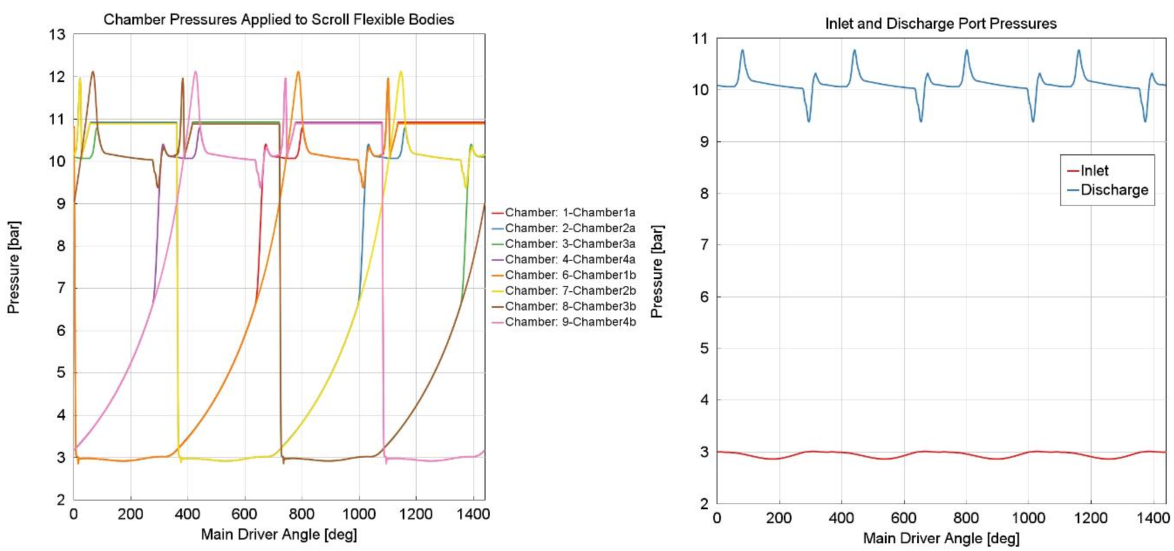

Figure 3: Scroll chamber and inlet and discharge port pressures predicted for an 8-chamber scroll compressor

4.2 Application of chamber pressure loads

To simulate dynamics, forces and deformations of moving parts of a scroll compressor and loads on all supporting bearings, compressor chamber and intake/discharge pressure loads have to be applied. The current methodology automates this process for MBD modeling with both rigid and flexible body analyses.
In addition to chamber areas and volumes, the pre-processing step referred to in the previous section also calculates and pre-stores chamber cross-sectional areas, centroid locations and effective in-plane force directions as a function of scroll crank angle. This allows automatic calculation and summation of all 3D forces (Fx, Fy, Fz) and moments (Mx, My, Mz) on each scroll on an instantaneous basis, and their application on scroll bodies, in analyses where scrolls are treated as rigid inertias.
The task of applying chamber pressure loads for flexible MBD analysis, in which various bodies are discretized using FE, is more complex and requires knowledge of which pressure (chamber ID, intake or discharge port) each surface node on FE mesh surfaces is "mapped" at each angular position of the crank. This "node-to-chamber mapping" information is also generated and embedded in the model as part of the same pre-processing automation step described earlier, based on user-supplied scroll FE models. As a result, the correct chamber (or port) pressure is automatically applied at every node exposed to gases during the MBD simulation.

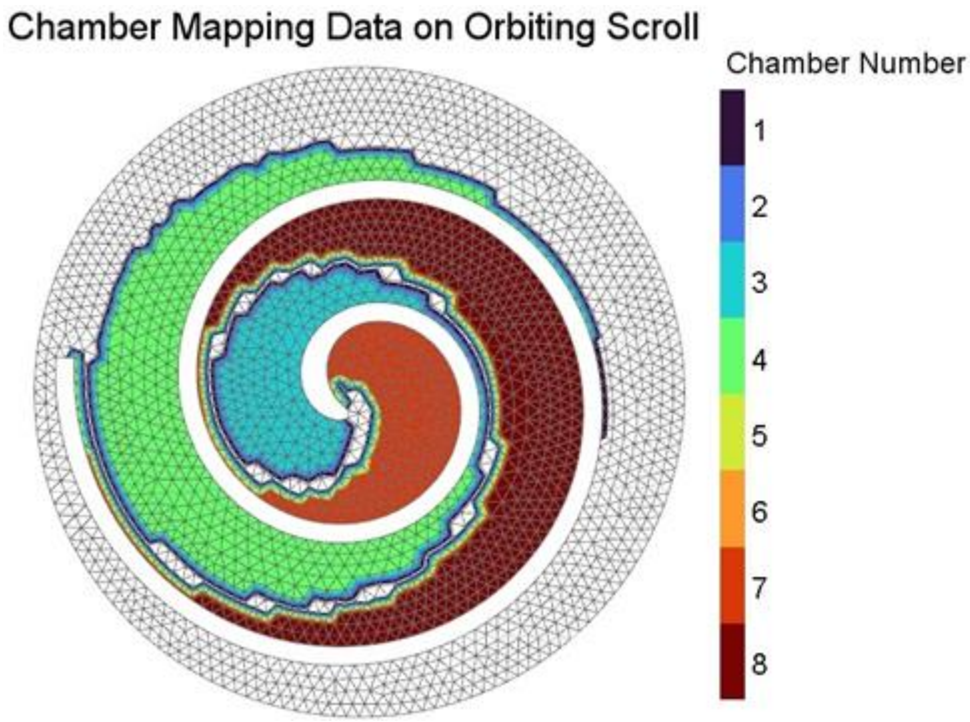

Figure 4: A snapshot (frame) from an animation of node-chamber mapping information for the orbiting scroll of an 8-chamber scroll compressor (top view, scroll flanks also mapped). Colorless regions near the periphery are mapped on inlet port pressure.

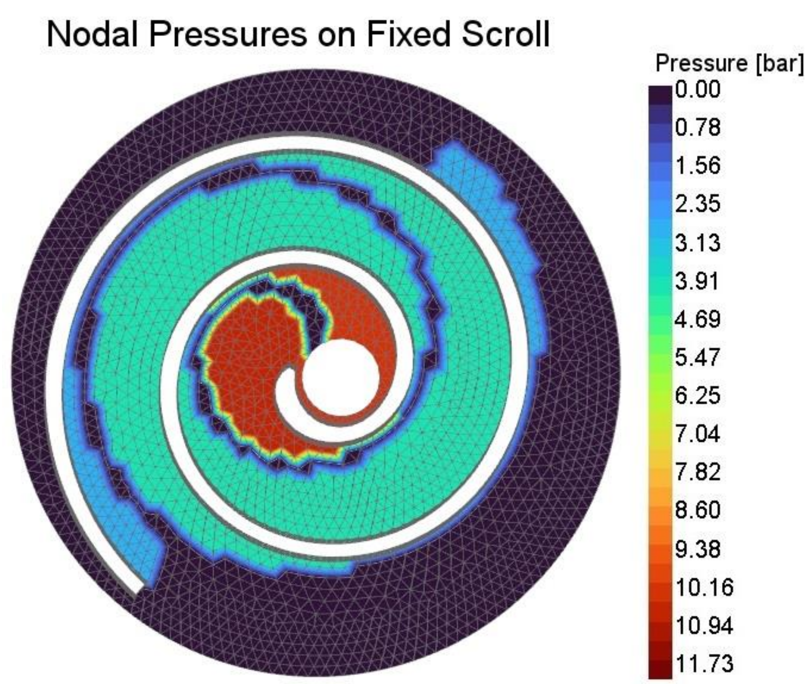

Figure 5: A snapshot (frame) from an animation of pressure applied to surfaces of the fixed scroll of a an 8-chamber scroll compressor

4.3 Dynamics, contacts and deformations

The key elements of a scroll compressor mechanism are i) the crank with offset crankpin; ii) the orbiting scroll; iii) the fixed scroll (which may be integral to the housing or have some room for axial motion; iv) coupling parts ensuring scrolls do not rotate. As shown in Figure. 1, the crank, driven by a motor, is typically supported by two journal bearings. The orbiting scroll is driven at the offset crankpin to which it is coupled through another journal bearing. Its back is supported by a housing surface that acts as a thrust bearing.

For solving the motions and forces in the scroll compressor, the integrated tool relies on its full-featured 3D multi-body dynamic library. Depending on the objectives of the model, bearings and joints can be modeled using standard MBD (revolute, prismatic etc.) joints, detailed 3D contact elements, and where applicable, tribological (fluid film) elements. 3D contact and fluid elements can be used with both rigid and flexible bodies representing crank, scrolls and housing. One MBD model configuration for the scroll compressor considered in this paper, is shown below in Figure. 6. For flexible scrolls four separate distributed 3D contact elements are used to model contacts between base, crown inner and outer flank of one scroll and the crown, base and outer and inner flanks of the second scroll respectively. The algorithms for the solution of distributed contact forces are highly optimized to conserve both operations and memory and in this respect makes use of the limited relative motion (orbit) between the two scrolls. Contact surfaces paired in two of these contacts are shown in Figure. 7 below for two meshed simple scroll geometries. Figure. 8 show contact gap and pressure results for scroll-to-scroll and scroll-to-housing (thrust bearing) contact elements at selected crank rotation angles. These are frames extracted from full-cycle (e.g. 1440 or 1800deg) animations.

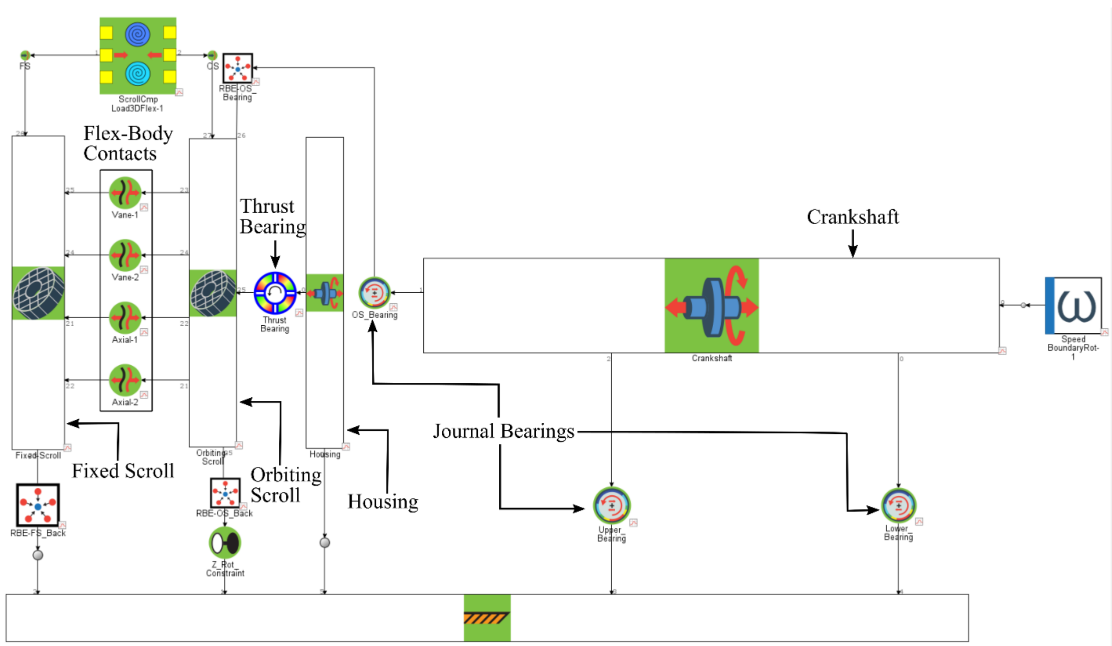

Figure 6: Symbolic view of multi-body dynamics model of scroll compressor assembly (flexible scrolls, rigid housing and crank)

Figure 7: Pairs of surfaces in contact in two of the four scroll-to-scroll contact elements used for modeling flexible body contacts (crown-base and inner-outer flank are flipped for the other two)

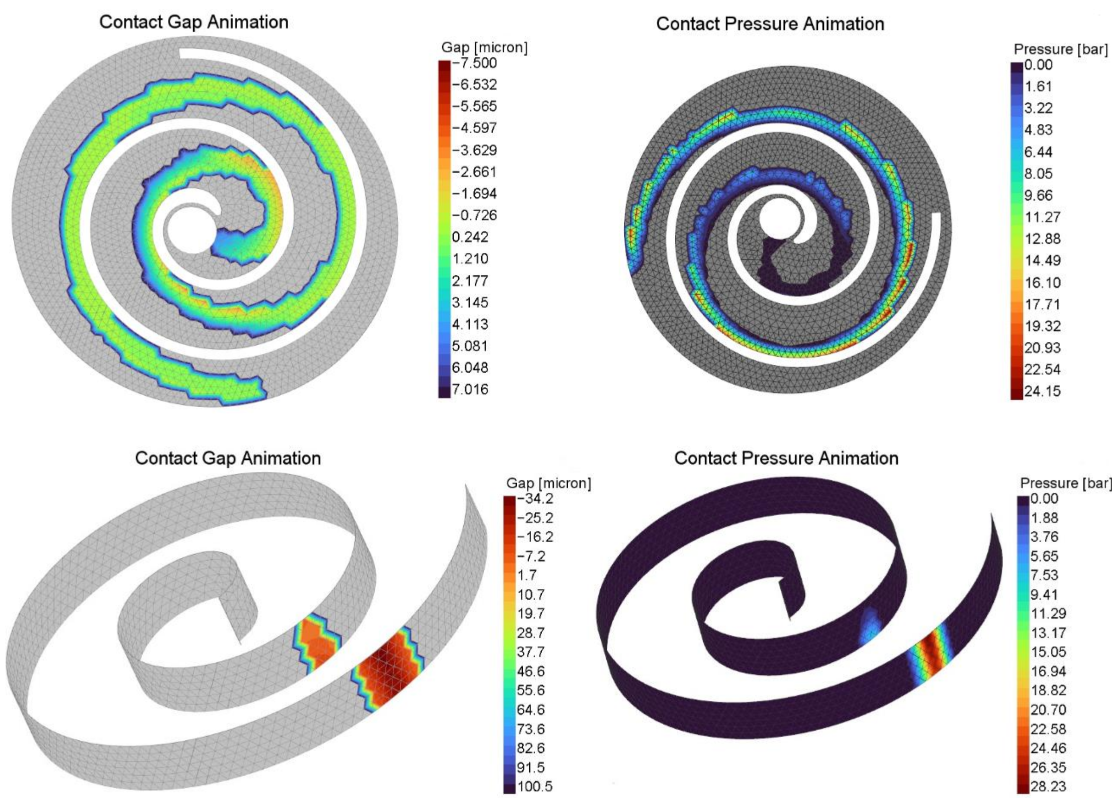

Figure 8: Snapshots (single frames) from contact gap (interference) and pressure animations for selected contact element pairs. Top: orbiting scroll crown to fixed scroll base contact, contours shown on fixed scroll base; Bottom: fixed scroll outer flank to orbiting scroll inner flank, contours shown on orbiting scroll inner flank

5. FLUID FILM BEARINGS, TRIBOLOGY, AND WEAR

An important element of the integrated approach is the analysis of mixed lubrication of journal and thrust bearings in scroll compressors. This allows realistic simulation, for given steady-state or transient speed and load, of lubrication conditions, friction power loss and wear load due to possible metal-to-metal contact, which can be further used for wear modeling and durability studies. The bearings in questions are i) the (typically two) journal bearings supporting the crank shaft; ii) the orbiting scroll journal bearing; and ii) the thrust bearing on the housing surface supporting the orbiting scroll axial load. Journal and thrust bearing film solutions are *hydrodynamic* (HD) when coupled to rigid bodies, i.e., rigid body states define the film and aggregate load computed by the mixed lubrication model is applied to the bodies as lumped forces. In the case of flexible bodies, the film solution is *elasto-hydrodynamic*: the film is defined by *both* body motions *and* deformations, and the resulting film (pressure) loads are *distributed* on the flexible bodies. Figure. 9 below shows a rigid crankshaft with the three HD journal bearings mentioned above integrated with the thermodynamics scroll model.

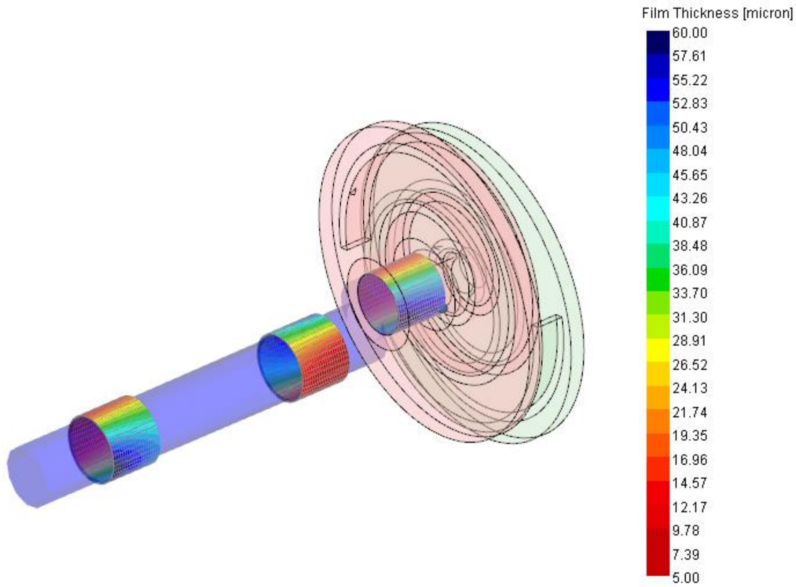

Figure 9: Snapshot (single frame) of crankshaft with two supporting bearings, orbiting scroll bearing showing the oil film thickness

For predicting film pressure distributions, the mixed lubrication model relies on an FE-based solution algorithm for the Reynolds equation for films in conformal interfaces, applicable to general (e.g. flat, cylindrical, etc.) topologies and lubricated domains defined by arbitrary boundaries. It is run in conjunction with the Greenwood-Tripp asperity contact submodel (Greenwood & Tripp, 1970), based on a statistical representation of surface roughness and elastic properties, which predicts distribution of average roughness (asperity) contact pressure. Its additional features allow modeling of transient pressure boundary conditions and of various physics (all coupled) known to affect film lubrication: i) cavitation and mass conservation (Kumar & Booker, 1991), ii) heat transfer and oil temperature rise; iii) effects of temperature, pressure (Barus or Roelands eqs.), shear rate (Carreau, Cross, Modified Cross or Carreau-Yasuda shear thinning/thickening models) and presence of mixed refrigerant (Daniel Chart approach, (Henderson, 1994)) on viscosity and density; and iv) effect of surface roughness (Patir & Cheng, 1978) or engineered surface micro-textures on film hydrodynamics. The algorithm uses state-of-the-art sparse-matrix algebra, parallelization and other numerical measures designed to speed up solution without compromising accuracy.

1D flow submodels of passive or active oil supply systems, including pumps, lubrication circuits, including the effect of moving/rotating parts etc. can also be integrated in the overall model, for prediction of pressure boundary conditions at oil supply points (holes, grooves etc.) for bearings (James & Mlsna, 2023)

5.1 Housing Vibrations, Noise

The integrated model also allows coupling of a flexible scroll compressor housing structure 3D FE model, for purposes of vibration and acoustic analyses. Scroll, journal/thrust bearing and coupling component loads on the housing, calculated by the MBD and HD/EHD models and assembled on the housing model yield housing vibration predictions. This can be done in the same model, but more typically (for more efficient processing) handled via automatic export/import of all housing loads for use in a separate NVH model of the housing structure, run in the frequency domain. A fast, meshless acoustics model, shown to be accurate for blunt or mostly convex bodies such as pumps, compressors or transmission housings and engine blocks, can also be run in series with the vibration to predict radiated noise spectra at specified locations.

6. MODEL SETUP AND COMPUTATION TIMES

With the help of the preprocessing tool described in section 4.1, a ready-to-run 1D flow model coupled to an MBD model of key elements common to most scroll compressor configurations (fixed and orbiting scroll, crankshaft and housing, joints, or contacts) can be generated in a matter of minutes. The same tool also generates 3D FE meshes, at the desired levels of resolution, of the scrolls and other components modeled as flexible bodies, starting from 3D solid models. It also allows the user to separately identify surfaces representing scroll base, crown, back, inner /outer flank etc. on the generated meshes. Additional elements pertinent to specific designs (e.g. couplings, contacts etc.) can be easily added to the model within the symbolic user interface shown in Figure. 6, using standard 3D MBD library elements.

The flexible bodies used in the MBD methodology are aimed primarily at the calculation of deformations, and their effect on bearing surfaces and leakage gaps, vs. detailed stress calculations. Consequently, low to medium mesh resolutions were found to be appropriate. Computational time will vary on the number of flexible bodies beyond the scrolls (e.g. crank), on the mesh resolution used for both flexible bodies and bearing oil film solutions, on whether oil film solutions are hydrodynamic or elastohydrodynamic, and on the number of scroll chambers (i.e. 6, 8, or 10). For results presented in this paper, two sets of resolutions were used for the scroll bodies: Approximately 4,500 nodes and 16,000 tetrahedral elements were used for coarse-resolution scroll models, while high resolution scroll meshes had ~14,000 nodes and ~50,000 tetrahedral elements. Completing the calculation of 1 compression cycle (1440degrees) for the 8-chamber compressor modeled with the coupled 1D flow-MBD model with a rigid crankshaft and lower-fidelity (Reynolds Eq. mesh resolution) hydrodynamic film computations for journal and thrust bearings required two to four hours on a laptop with 64GB RAM, 12^{th} GEN i7 with 24 cores and 16 threads, depending on mesh resolution for scroll flexible bodies. An integrated model with higher resolution bearing film hydrodynamic solutions took six to eight hours. This compares favorably with FEA+CFD workflows which involve *days* of simulation time. Also note that idealized scroll-compressor geometry will result in pressure distributions, flow rates and mechanical loads that repeat every 360degrees, which affords users of the workflow the option to limit simulation duration to 360 degrees of crank rotation.

7. SUMMARY AND CONCLUSIONS

This paper illustrates a novel approach to analyzing a scroll compressor by modeling all physical domains (compression thermodynamics, dynamics and deformation of moving parts, and bearing oil film hydrodynamics) along with interactions between them, under transient conditions as an all-in-one solution, within a single multi-physics platform and workflow which also features a time-saving automated pre-processing tool dedicated to scroll compressor model generation starting with 3D Solid models. The approach also offers flexibility in fidelity levels for each sub-system, and can thus be tuned to the objective of the analysis. The primary application of the coupled workflow is to model the effect of scroll and crank deformations on the operation and integrity of journal and thrust bearings and on scroll contacts, sealing and leakages. The workflow offers significant automation, usability and runtime benefits compared to FEA+CFD approaches based on co-simulation with multiple tools, and is a more practical alternative that lends itself to parametric studies and optimization studies, empowering design engineers to achieve shorter product development time, less prototyping, and reduced testing costs.

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