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LOOK AT HOW, WHEN AND WHY THE SIMULATION OF COMPLEX PROCESS MACHINERY INTERACTIONS SHOULD BE UNDERTAKEN IN HYDROCARBON PROCESSING PLANTS.

A REFLECTION OF REALITY

The design of complex oil and gas processing facilities is becoming ever more dependant and subject to safety analyses, within which dynamic transient behaviour is an essential issue. Hazardous operation (HAZOP) meetings are now milestones in new project developments. It is in these situations where issues are discussed and where questions regarding emergency or normal plant shut down procedures are raised. Often, these questions cannot be answered by simple logical flow analyses, because they rely on quantitative information about the response of a plant to routine and emergency manoeuvres: machine speed, fluid pressures or temperature

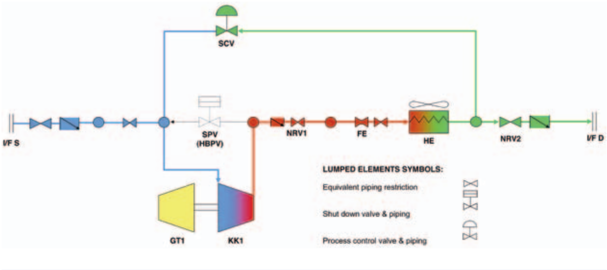

Figure 1. Case study one: simplified depiction of the gas compressor.

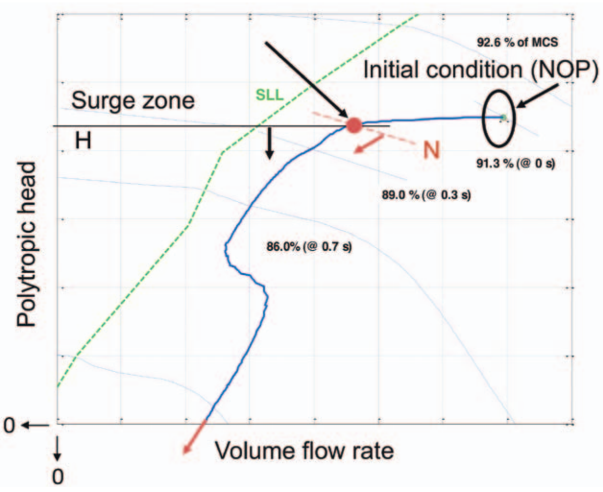

Figure 2. Operating point path during an ESD: compressor map in 'corrected' coordinates (normalised units).

reactions to certain automatic or operator actions (overshoots, trends and settling out values).

This information cannot be easily calculated for increasingly complex plants where there are many physical phenomena and control systems, often with subtle interactions, propagating over areas of the plant which may appear immune from impacts. For many years, the analysis of these phenomena has been the object of dynamic simulations based on physical mathematical models. Yet, they were often implemented too late in the project development to verify plant design at an advanced stage. Delaying these checks can cause a serious overrun of costs when evidence of required changes emerges. Taking into account both equipment cost and delivery time, a potential delay in start up or even later modifications, these costs quickly become out of hand.

Therefore, dynamic simulation studies (DSS) are increasingly becoming a priority in project planning, particularly in circumstances that require a complex trade off between plant and equipment data availability on one side and model feasibility and accuracy on the other.

Tools for DSS

A number of commercial software tools for processes DSS exist on the market,[1] yet few of them treat machine dynamics and mapping in a fully dynamic sense during a simulation. One technology that offers turbomachine map changes with inlet gas conditions variation during a simulation is COMPSYS™.[2 - 6] This software also features the Starling modification of the thermodynamic Benedict-Webb-Rubin (BWRS) equation of state (EOS), which has the highest accuracy for gaseous hydrocarbon components[7, 8] and instantaneous calculation of fluid transport properties and heat exchange coefficients.[5, 6]

However, having access to a powerful dynamic simulation tool does not guarantee the usefulness of simulation. On the contrary, misuse of the simulation environment may lead to disastrous results. Some potential issues are:

Data management

Two of the most costly aspects of a simulation job are the extraction of data from client and equipment suppliers' documentation and entering parameters according to the software input data formats. Moreover, an appropriate file system and file management, cross referencing of results, and details of the model used, kernel software version and output are all essential to ensure the production of reliable and repeatable results.

Modelling approach

Commercial software tools are tailored to categories of problems with their own dynamics bandwidths. This often makes it difficult to modify or add features to cope with the specific functionalities of a new system architecture (see case study two). Conversely, general purpose modelling environments, such as the Matlab/Simulink* suite allow the consulting company to closely follow the needs of the project, adding bespoke features and eliminating inessential components, adapting the mathematical solvers to the accuracy required.

Numerical solvers of ODE

Low order solvers are often preferred for fast calculations. However, this can lead to totally erroneous results that are not always apparent as rough plots.[4] One such example is obvious numerical instability cases. Smooth plot lines can be misleading, as they may be wrong due to error propagation and drift of ordinary differential equation (ODE) results along with a simulation. This is why higher order solvers, particularly with variable time step, should be preferred for DSS.

Calibre of personnel

Finally, the background and experience of the personnel utilising these tools is essential. Although simulations rely on sophisticated algorithms and software environments, it is nonetheless certain the engineers must possess the requisite robust notions of mathematics and informatics. The real life components of the simulated systems are mechanical, electrical process systems, which must be understood by the simulation personnel beyond the virtual reality of their tools. A DSS requires every team member to apply a multidisciplinary mind both individually and collectively: in mechanics, thermodynamics, electrical, controls, signal processing, as well as in mathematics and computer programming.

Not all original equipment manufacturer (OEM) companies can afford the costs of such an engineering team, especially if the simulation required exceeds the product responsibility of the OEMs, as is often the case.

Simulations are system engineering tools, which should be used at the appropriate level of integration, regardless of the border of supply responsibility. A DSS should be assigned to specialised third party companies by those with responsibility at the system engineering level. These third parties generally have extensive experience, with a variety of systems simulated in their portfolio, and are therefore better equipped to take on the task than compartmentalised OEM personnel.

DSS management

The decision as to whether to integrate DSS in a project should be taken as early as possible in a project, giving the study a staggered approach and budget, typically with three phases.

Following the front end engineering and design (FEED) phase, a DSS can help in identifying possible critical areas, such as the choice of machines (in particular drivers and compressors that would constrain the process design), which cannot purely be chosen from steady operation data. Simple models can be adopted in this phase, even without full implementation of the control system or even with open loop components.[5, 6]

Another important phase where DSS can be conducted is prior to defining or confirming the piping layout, as soon as the first version of isometric drawings is available. The aim of this is to ensure a more accurate modelling of the physical plant, while not being entirely accurate for the control system. This would allow the correction of possible inadequacies in the volumes, valves positions and pipe routing, avoiding much more costly fixes of surge prevention problems later on. For example, hot bypass lines can be added or surge control valves (SCV) repositioned.

Finally DSS should be planned, with the most accurate model of the piping, equipment and control system, for the verification of all operational procedures regarding process and machines and their transient behaviour. Another useful and economical result of the DSS in this phase is the preliminary tuning of the controllers, which is necessary anyway for the correctness of the simulations. This reduces the infield activity of control engineers, as they can start their tuning job from default parameters that are already close to optimum, upon the fidelity of previous modelling.

The above phases can also be appropriately planned or further split according to HAZOP measures, which themselves are augmented by the information gleaned from a DSS.

Based on this approach, a DSS can be cost effective, giving the engineering managers sufficient time to qualify suppliers and, after the execution of the DSS, allowing proper design correction at a low cost.

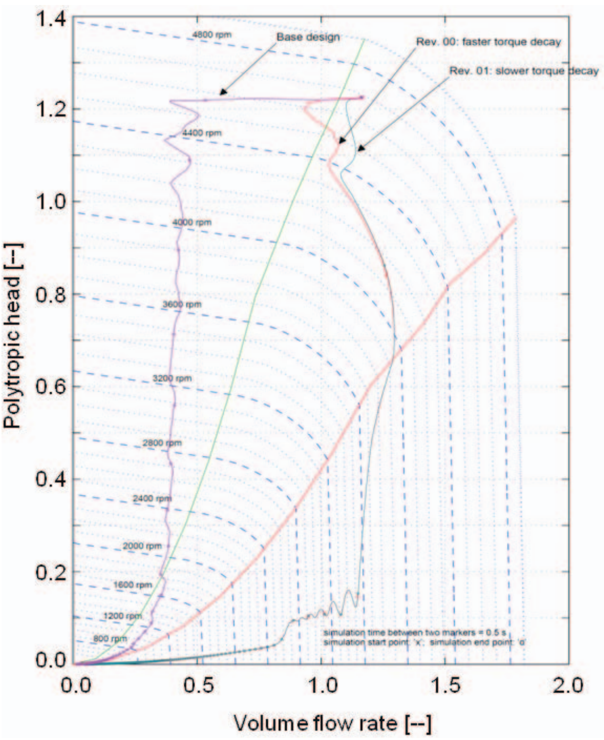

Figure 3. Case study one: compressor operating point (normalised units). As built, without hot bypass (magenta); as made after DSS, with hot bypass under the fastest (red) or slowest (black) driver torque decay rate.

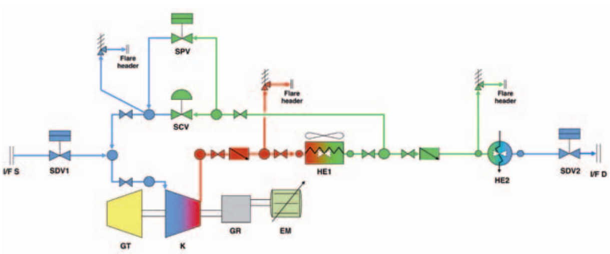

Figure 4. Case study two: simplified depiction of the modelled NGL extraction and liquefaction compressor.

Case study one: compressor surging

A problem often identified too late in compressor installation design is the layout and size of antisurge lines and, in particular, the need for hot bypass valves (HBPV) to safely manage emergency shutdown (ESD) events.[2, 3, 5, 6]

This case study exemplifies the issue, focusing on a gas compression system composed of several parallel compression trains of identical plant layout, each driven by a gas turbine. For the verification of the surge protection a single train model is sufficient, since this event causes an almost immediate isolation of the utilised compressor, due to the shut off of check valves and closure of isolation valves (Figure 1).

The ESD dynamics cannot be predicted by manual or spreadsheet calculations because of the rapid interaction between the discharge piping depressurisation, the train speed fast drop and the fast movement of the operating point of the compressor through the characteristic map.[2]

Due to the speed reduction, the instantaneous speed line drops rapidly along the map, as evidenced by the moving characteristic line 'N' in Figure 2. At the same time, the discharge pressure and the compressor polytropic head decrease (line 'H') depending on the speed, size and volume of the piping and equipment on the discharge side of the compressor up to the nearest check valve.

Consequently, the instantaneous volume flow rate delivered by the compressor and the operating point on its map (determined by the intersection between the moving lines 'H' and 'N') will move leftwards, approaching the surge limit line; or rightwards, departing from the surge limit line, depending on which of the two lines drops faster during the transient.

In the first part of the event (the first 100 - 300 milliseconds) it is usually the speed line that will move faster. During this time interval it is essential that the SCV and protection valve open quickly in order to depressurise the piping as fast as needed, thus maintaining the operating point at a safe distance from the surge limit.

The problem is complicated by the concurrent importance of several factors that affect the result of an ESD:

- Train rotational inertia: the larger it is, the slower the speed coast down rate.
- Discharge piping volume: the smaller it is, the faster the depressurisation of the discharge side and the reduction of the polytropic head.
- Slope of the map characteristics at constant speed: the higher it is, the slower the flow rate reduction for a given speed coast down rate.
- Size of the SCV and/or surge protection valve (SPV or hot bypass): the larger it is, the faster the depressurisation of the discharge piping and the reduction of the polytropic head.
- Valve flow opening characteristic, whether equal percentage, linear or quick opening: the latter obviously provides a faster recycle flow onset.

- Dead time and delays of check valves closing and SCV or SPV opening: delay in check valve shut off causes a short time backflow from the delivery side, which reduces the effective promptness of SCV and SPV action.

Complexity increases because the compressor map changes according to the inlet temperature, which is the case when a hot bypass line is used.

The many non-linear physical interactions occurring among these factors imply that only high fidelity dynamic simulations can solve this apparently trivial line and valve sizing problem. A DSS shows that even apparently small variations in these parameters can completely change the result of the event: causing a surge or not.

Usually, SCV lines leave downstream aftercoolers, in order to avoid hot gas recirculation under the normal antisurge control action. This implies that the discharge side piping volume between the compressor nozzle (the T joint where the surge line takes off the nearby check valve, for example non-return valve (NRV) two in Figure 1) and the SCV are usually large. Flow inertia due to length of the antisurge line increases the reaction delay. In conclusion, preventing surge on ESD by means of the sole SCV is hard to achieve, as the SCV has to be very large in order to obtain a fast depressurisation. Besides its cost, other drawbacks of this solution are the reduced controllability of the SCV under normal control action. Under normal action, the SCV would work around almost closed position and the consequent fast flow through the aftercooler on ESD could damage its bundles.

The above arguments lead to the addition of a dedicated SPV just downstream the compressor, bypassing the hot compressed gas directly to the suction side. The volume between this, the SPV T joint and the nearby check valve (NRV one in Figure 1) is much smaller than the aforementioned, thus rendering surge prevention on ESD more effective.

This simple reasoning has as its counterpart a difficult, not always intuitive and often neglected, design process. This is why it is not uncommon to find gas compression facilities that are not suitably protected from surge, causing evident problems even shortly after commissioning.

Surge durations of a few hundred milliseconds are generally deemed acceptable by most compressor vendors. However, experience shows that many compression facilities are at risk of undergoing longer lasting surge conditions, which would damage the compressor.

In this case study, the compressors were built without hot bypass lines. During operation, an ESD was proven to have caused a severe surge, which raised questions about the correctness of the surge line design.

In this example, SATE was commissioned to undertake a DSS, which confirmed the need for a SPV (Figure 3, magenta line) and helped to find a convenient compromise regarding its size (Figure 3, red and black lines). The compressor vendor accepted the envisaged residual surge, which would last less than half a second. Needless to say, the cost for the plant modification was extremely high, weighing in at upwards of € 1 million. The much cheaper DSS could have avoided this economic outlay if performed during the early design stage, even before the definition of the piping layout.

Case study two: centrifugal compressor

The dynamic simulations for this case study concern a natural gas liquid (NGL) extraction and liquefaction recompression unit during normal and emergency operations (Figure 4).

Isolation valves bound the simulated plant model on the suction side and discharge sides (severe duty control valve (SDV) one and SDV two, respectively). The compressor was a single stage train with one air cooled aftercooler and one water cooled aftercooler, placed respectively upstream and downstream of the antisurge line take off.

The scope of the DSS was to identify the critical start up conditions of the compressor driveline string, including a gas turbine (GT) combined with a gear and a starter/helper electric motor (EM): the latter having to compensate for the lower power availability of the GT in summer conditions.

One particular focus was to identify the maximum settling out pressure (for example, after a shut down) at which point the system might not start and reach a stable, steady condition. The overall controlled system stability was then analysed to find conditions of unstable behaviour.

Another objective of the DSS was to verify the operating procedures for start up and, in particular, ensure compliance with the maximum revolution acceleration rates, which are determined acceptable by the driver string.

None of these investigations could be performed without dynamic simulations due to the complex, non-linear interactions among the various physical and control subsystems, combining both fast and slow changing phenomena.

In this case, the complexity of the start up analysis system is heightened due to the combination of an electric driver with a gas turbine. These respective technologies have very different torque speed characteristics and require a coordinated torque and speed control for smooth operation under speed and load changing.

In one typical start up simulation setup, the SCV was set to switch to anti surge control (ASC) when the nominal driver speed was reached. The run initially started with equal pressure and temperature throughout all the piping and equipment volumes bounded by the isolation valves. These valves (SDV one and SDV two) remained closed during the first part of the operation, with the plant depressurised.

The driver's torque controllers had to adjust the torque in order to comply with a given ramp sequence and with the following logical constraints:

- The GT runs at full torque capability until it reaches the minimum driver operating speed (MOS), which is 95% of the

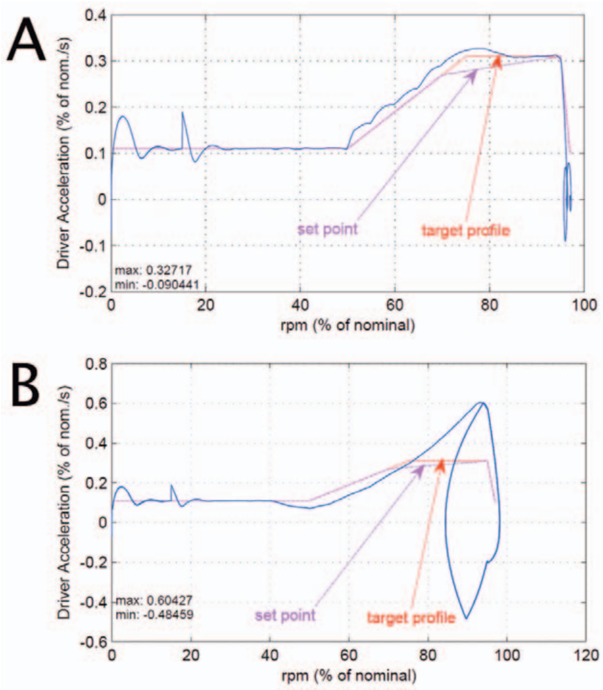

Figure 5. Case study two: driver acceleration versus speed during normal start up from depressurised conditions, from pressure below (A) and above (B) the instability starting pressure threshold, identified by DSS.

nominal driver speed. Instead, the GT follows the speed control output when running above that speed.

- The EM is disabled (delivering no torque) when both the following conditions are satisfied:
  - The speed is higher or equal to the compressor nominal value.
  - The GT torque is lower than a given threshold from the maximum deliverable at the instantaneous speed.

This simulation ended at stabilised 97% speed conditions in full recycle with the SCV fully open. In depressurised condition, the DSS results showed that there was a maximum start up pressure of the plant from which the GT and the EM were jointly capable to start the compressor and reach a stabilised condition at 100% speed (Figure 5a). Below that pressure the drivers can follow almost the same speed ramp and reach 100% speed in approximately 10 minutes. When starting above that pressure, the train speed does not correctly follow the set point ramp, showing periodical instability by exceeding the acceleration limits (Figure 5b).

The instabilities occur around the MOS because the GT cannot maintain its full torque capability given the rate limits imposed to both the GT and EM controllers. This causes the sudden loss of torque by the GT, as is not compensated quickly enough by the EM controller. Thus, this result allowed the specification of these limits, and the safe margins thereof, in the operating procedures of the compression system.

Conclusion

Undoubtedly, design is always an iterative and idiosyncratic process. Therefore, there is no single moment in a project where DSS should be placed. The actual design and conception of a system is the result of a human thought and planning and simulations should always be viewed as a feedback activity oriented to helping a given task towards the most convenient solution. The case studies cited are spots of experience to illustrate what solutions can be offered to reduce time and cost when proceeding with a correct, safe, clean and energy efficient contemporary system design.

Notes

Matlab and Simulink are products by Mathworks Inc. (Natick, Mass., USA). SATE is a member of the Mathworks Partners Programme. COMPSYS is based on the Matlab and Simulink platform.

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