AVOIDING RESONANT FREQUENCIES IN A PIPELINE APPLICATION BY UTILISING THE CONCEPT DESIGN ANALYSIS METHOD

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Abstract

Avoiding disasters due to the problems stemming from resonance is a major concern in any construction project. This becomes particularly important for oil and gas pipeline systems as some damages may lead to leakage of flammable fluids, explosions, fires, destruction and loss of life. The proximity to the natural frequencies of forced frequencies (frequency ratio) normally leads to intolerant resonant vibrations and catastrophic failures. A relevant case study on a partial pipeline design with an unacceptable level of frequency ratio is presented. In order to assess the overall design merit of the case study, the Concept Design Analysis (CODA) method is utilised to map captured Customer Needs (CNs) into Engineering Characteristics (ECs). As the frequency ratio is an important EC of the whole system, the improved CODA method for the pipeline design introduces an avoidance type merit function that allows excluding a range of relevant ECs. This improved CODA method is demonstrated in a model whereby certain frequency ratios are successfully avoided in the final design.

Keywords: Systems engineering (SE), Design methods, Optimisation, Avoidance Function, Frequency Ratio

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1 INTRODUCTION

Designing complex engineering systems is immensely challenging. While Systems Engineering (SE) (Sage, 1992) standards, such as ISO 15288 (ISO/IEC, 2008) and the INCOSE SE Handbook (INCOSE, 2011), are helpful to structure the necessary activities dealing with complex problems, they expose to the risk of losing track of customer and stakeholder needs during design (Collopy and Hollingsworth, 2011) hence losing the ability to identify solution directions able to maximize the value generated by a solution. This has led to an increasing level of awareness and interest in value assessment as being an integral part of SE practices. Recently value models have become a standard feature in several development programs, especially in the aerospace domain (Castagne et al., 2009, Curran, 2010, Cheung et al., 2012, Price et al., 2012). The main reason is that they become appealing for system manufacturers to elaborate, early on, a concise, overarching cross-system requirement specifications list that clarifies the context and underlying intent of requirements during the preliminary design phase of a new system (Bertoni et al., 2014). The identified risks and issues related to early development work prior to having validated input requirements may be effectively mitigated, thereby reducing overall development times and costs, while improving quality and stakeholders' perceived value (Isaksson et al., 2013).

However, even though several value-driven approaches have been described, the majority of them focus on the economic aspects of value only (Collopy, 2012), as they are centred on the use of monetary models, such as the Net Present Value (NPV) and the Surplus Value (SV) models. This poses several challenges to designers (Soban et al., 2011), because quantitative economic functions are dependent from the availability of historical data, which are typically missing when performing a preliminary screening of new product technologies or services (Isaksson et al., 2013). Rather than focusing on the monetary aspects of value, several studies (Bertoni et al., 2013, Eres et al., 2014) have expressed a preference towards a different approach to capture the value contribution of a design, based on the opportunity to capture, consolidate and prioritise external and internal stakeholder needs (that may be based on concrete customer needs and expectations) and to link them to the product's engineering characteristics.

The use of a more subjective definition of value and of qualitative predictive models becomes interesting then to enable what-if assessment loops to be executed at a higher pace, and at all levels of the supply chain. However, few real-life examples of these qualitative models can be observed, and most of the approaches remain only at a conceptual level of maturity.

2 OBJECTIVES

With the purpose to grow the understanding of how qualitative value models can be used in practice to support the early design stage of a complex system, the paper aims to describe, observe and assess the implementation of one of such models in a real-life example. The objective of this work is therefore to describe the application the Concept Design Analysis (CODA) method (Woolley et al., 2001, Woolley et al., 2000), to support the early stages of the design of a pipeline system. After presenting the criticalities related to the design of a pipeline system, the paper describes the CODA methodology in detail and how it has been customized and adapted to model such criticalities in the value assessment process. Eventually, the results obtained by the modelling activity are presented and discussed, and pointers to future research are presented.

3 CRITICALITIES IN THE DESIGN OF PIPELINE SYSTEMS

Avoiding disasters due to the problems stemming from resonance is a major concern in any construction project. Many oil and gas facilities contain sources of vibrations, such as pumps, compressors, separators, and so on. Similarly, parts of oil and gas facilities are also subject to natural external vibrations, such as pipelines, spans, and risers. All structures have natural resonant frequencies that depend on design calculations. The resonant vibration will take place when damping is small and the external initiator frequency (forcing frequency) is approximately equal to the natural frequency of the system. These resonant vibrations increase the amplitude of the waves and may be the root cause of structural failures and disasters. These failures are especially important for oil and gas pipeline systems as any damage may lead to a leakage of flammable fluids, explosions, fires, destruction and loss of life (Anonymous, 2014). National standards usually demand that these effects are considered during the design process:

- "Spans in pipelines shall be controlled to ensure compliance with the strength criteria in 6.4.2 (such as general, yielding, buckling, fatigue, and ovality). Due consideration shall be given to: ... possible vibrations induced by wind, current and waves (BS EN 14161:2003, p. 22). Vibrations caused by vibrating equipment, fluid pulsations from reciprocating pumps or compressors and flow induced pulsations shall be considered during the piping design" (Anonymous, 2003).
- "Pipe and riser spans shall be designed so that vortex-induced resonant vibrations are prevented, whenever practical. When vibrations must be tolerated, the resulting stresses due to vibration shall be considered in the combined stress calculations in para. A402.3.5 (a). In addition, calculated fatigue failure shall not result during the design life of the pipeline and risers." (Anonymous, 2010).
- "The main criterion to ensure vibration strength of the pipeline is the avoidance of convergence its natural frequencies and external initiator frequencies due to load, determined in accordance with para. 2.2." (Anonymous, 2007).

The design requirements for avoiding resonant frequencies of pipelines are expressed using frequency ratios and they have the following mathematical form (Anonymous, 2007):

$$0.75 \geq \frac{f_{ip}}{f_j} \geq 1.3, \quad j = 1, 2, 3 \tag{1}$$

$$0.9 \geq \frac{f_{ip}}{f_j} \geq 1.1, \quad j = 4, 5, \ldots \tag{2}$$

where f_{ip} is the forcing frequency by external initiators (pumps, compressors, etc.); $ip = 1, \ldots, IP$; IP is the number of external initiators of harmonic oscillations; f_j is the pipe's natural frequency; $j = 1, \ldots, J$; J is the number of pipe's natural frequencies of harmonic oscillations.
The first harmonic f_1 has the lowest natural frequency and it is the most critical. Harmonics above the third pose less risk to the pipeline, because they have a smaller magnitude. Transmissibility is the dimensionless ratio of output to input in vibrations. Transmissibility value more than unity means amplification of vibrations that begins before when the forcing frequency (f_{ip}) and the natural frequency (f_j) of the system coincide (Broch, 1984, p.44). The oil and gas standards determine two dangerous ranges of the frequency ratio, which should be avoided for pipeline design in accordance (1) and (2). In this study, five ranges of frequency ratio are allocated and they vary between intolerable to recommended ranges in accordance with the oil and gas standards (see Figure 1).

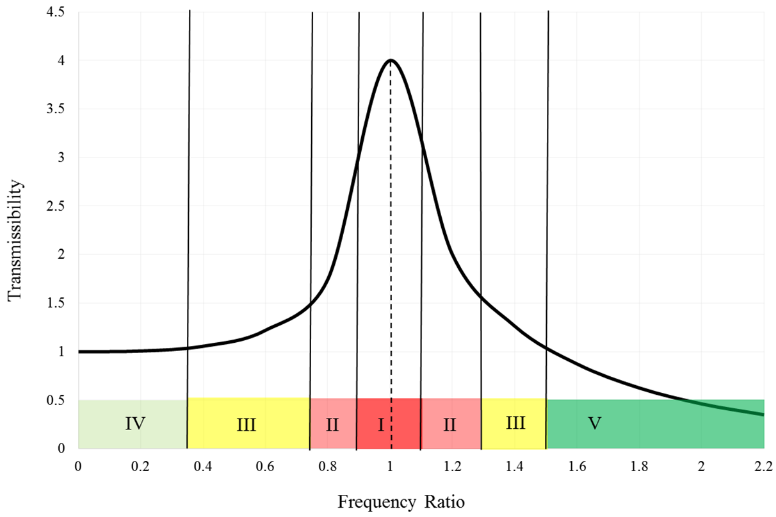

Figure 1. Frequency ratio ranges (I –intolerable range for all natural frequencies: II – intolerable range for 1st, 2nd and 3th natural frequencies: III – tolerable ranges; IV – recommended if range V is impossible; V – recommended range).

The natural frequencies of the pipeline span (diameter 325 mm, length 2 m, wall thickness 30 mm) have been determined using ANSYS software (Khamukhin, 2014). The results show many critical ranges of frequency ratios that have intolerable magnitudes. An overlap of the natural frequencies with the forcing frequencies under variations in the rate of rotation of the compressor shaft, in some cases, is achieved for the rate of rotation range from 1000 to 3000 RPM of two different compressors (four and eight cylinders). This overlap demonstrates that the frequency ratio must be yet another engineering dimension in the CODA method for the pipeline design. Hence, the avoidance function is the necessary tool for avoidance of intolerable values of frequency ratio in the CODA model.

4 USING CODA FOR EARLY STAGE PIPELINE DESIGN

The Concept Design Analysis (CODA) method allows mapping of captured Customer Needs (CNs) into Engineering Characteristics (ECs) and calculating an overall 'design merit' metric to be used in design assessments, sensitivity analyses, and engineering design optimisation studies (Eres et al., 2014). The original CODA method was first presented for optimising the development of a medical device (Woolley et al., 2001) and further deployed for preliminary aircraft design in an extended enterprise (Eres et al., 2014). The CODA method involves the three relationship functions between CNs and ECs: minimisation, maximisation, and optimisation type.

Representative merit functions for various ECs are presented in Figure 2, and exemplified using an aerospace product as an example (Eres et al., 2014). The maximum take-off weight of an aircraft or the sea level static thrust of engines can be modelled with a maximising function as higher values of these ECs correspond to higher customer satisfaction levels. On the contrary, specific fuel consumption of engines or the cabin noise level of an aircraft need to use a minimising function as lower levels of these ECs are more desirable. For some other ECs, such as the cockpit illumination level or the legroom in the economy class cabin, a target setting may be more appropriate and the optimising function offers a more viable alternative than minimising and maximising functions.

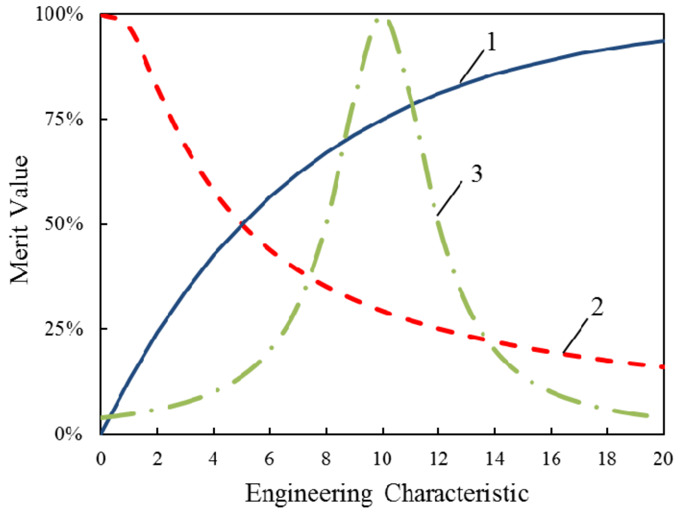

Figure 2. Representative merit functions for various engineering characteristics showing their effects on customer satisfaction levels: 1 – Maximising, 2 – Minimising, 3 - Optimising (Eres et al., 2014).

The frequency ratio ($f_{ip}/f_j \equiv Q$) is considered an EC in the CODA method for the pipeline design. In that case, there is a need for another merit function that allows excluding or avoiding a range of values for this EC in accordance with (1) or (2). The Avoidance Function presented by Khamukhin and Eres (Khamukhin and Eres, 2014) has been used to model resonance effects in the design and to exclude a range of frequency ratios that are potentially dangerous for the pipeline structure. The function is described by the following mathematical form:

$$f_{Avoid}(\rho) = 1 - \frac{1}{1+\left(\frac{\rho-\eta}{\tau}\right)^2}. \qquad (3)$$

Here, ρ is the value of the EC, η is the neutral point, and τ is the tolerance. When the EC is equal to neutral point, by definition the avoidance function has the value of zero. When the EC is equal to one of the tolerant values ($\rho=\eta\pm\tau$), by definition the avoidance function has the value of 0.5. This avoidance function is the inverse of the original optimising function and allows excluding or avoiding some of the values of the EC by returning very low values for the design merit, e.g., resonant frequencies when frequency ratio $Q = 1$ (see Figure 3).

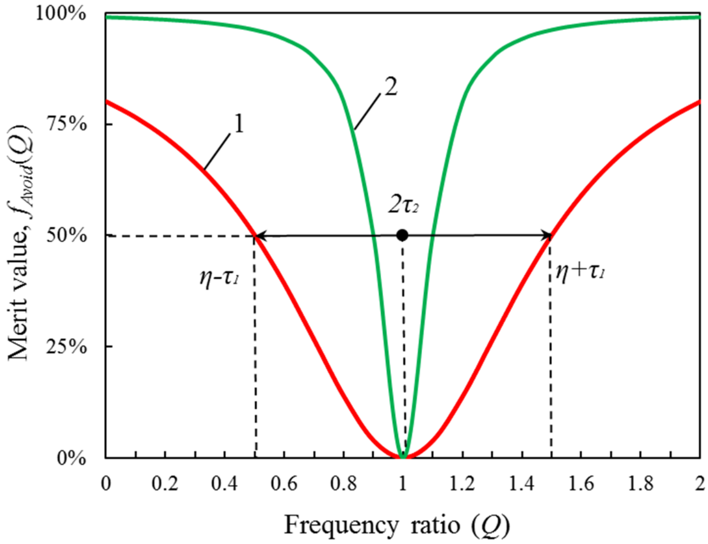

Figure 3. The effect of neutral point ($\eta = 1$), and tolerances on the avoidance function: (1) $\tau_1 = 0.5$, and (2) $\tau_2 = 0.1$.

4.1 Customer Needs

Looking at the customer needs (CNs) for a new pipeline, several dimensions appear to be desirable, such as environmentally friendliness, lightweightness, long service life, easiness of operation and maintenance, low operating costs, and so on. For the sake of brevity, the model presented in this study features only six CNs similar to CNs from (Eres et al., 2014) and they are: 1) Easy to extend operational life, 2) Green pipeline, 3) Cheap to maintain and repair, 4) Low capital expenditures (CAPEX), 5) Low operating expenditures (OPEX), and 6) High earnings before interest, taxes, depreciation and amortization (EBITDA). However, not every CN should have the exact same effect on the design concepts and usually CNs are assigned different weights to capture this variable influence (Eres et al., 2014).

	Easy to extend operational life	Green pipeline	Cheap to maintain and repair	Low capital expenditures (CAPEX)	Low operating expenditures (OPEX)	High earnings before interest, taxes, depreciation and amortization (EBIDTA)	X scores	Y Scores	Total score	Biased score	Normalised score
Easy to extend operational life		0	0	1	1	0	2	0	2	3	15%
Green pipeline			1	1	1	1	4	1	5	6	30%
Cheap to maintain and repair				0	1	0	1	1	2	3	15%
Low capital expenditures (CAPEX)					1	0	1	1	2	3	15%
Low operating expenditures (OPEX)						1	0	0	0	1	5%
High earnings before interest, taxes, depreciation and amortization (EBIDTA)							0	3	3	4	20%
	0	1	1	1	0	3				20	100%

Figure 4. A simplified version of a binary weighting model for a pipeline.

In this study, a binary weighting method has been utilised (Eres et al., 2014). By definition, the binary weighting matrix W is an upper triangular square matrix, and if the CN on the row is inherently more important than the one in the column, a numerical value of one is used. Similarly, when the CN on a row is decided to be less important than the one in the column, a numerical value of zero is used (Eres et al., 2014). This method allows the designer to assess the importance of CNs in pairs. A simplified example of a binary weighting model for a pipeline is presented in Figure 4. These CNs are identified in the very early stages of the design process, and represent the main criteria upon which the value of a pipeline concept will be assessed. The number of six CNs was considered as a sensible compromise between simplicity and detail, allowing the drivers to be managed without being overwhelmed with too many details. This binary weighting was used to model the relative importance of these CNs, based on the information provided by the pipeline manufacturer.

4.2 Engineering Characteristics

A CODA model allows the designers to systematically modify tangible and measurable ECs and to immediately see their effects on the overall design merit of the product. This approach enables designers to perform a wide range of analyses, such as trade-off and what-if studies, sensitivity analysis, and engineering design optimisation (Eres et al., 2014). There are many ECs of a pipeline design. Some of these ECs are selected in order to demonstrate the usefulness of the avoidance function. The relevant ECs for the pipeline design are presented in Table 1. And, the CODA method has been used to map these ECs to the previously identified CNs and to calculate the overall design merit value using the avoidance function for the EC called "Frequency ratio".

Table 1: Details of engineering characteristics of the pipeline design.

ECs	Units	Value	Lower limit	Upper limit
High strength pipes (Yield strength)	H/mm^2 (MPa)	448	250	690
High-grade corrosion-resistant steel pipes (Corrosion rate)	MPY (Mils per year)	2	0.5	5
Full gas pipeline capacity	billion cubic meters per year	13	6	16
Frequency ratio	Dimensionless	1	1.3	0.75
Pipe diameter	mm	720	114	1420
Inlet pressure	MPa	9.8	1.18	24.52
Span length	m	3	2	20

4.3 Pipeline CODA Model

The purpose of the demonstration activity was to benchmark design concept using avoidance function against an existing design concept without avoidance function. The pipeline CODA model needs to be filled according to the CODA step 4 (Eres et al., 2014). The experts have to span through all ECs in the model and identify any correlation and relationship type between them and the CNs. Then the model needs a neutral point to identify where in the solution domain 50% customer satisfaction is achieved (for minimisation or maximisation type relationships) (Eres et al., 2014). In addition, the model needs a tolerance value to identify where in the solution domain 50% customer satisfaction is achieved (for optimisation and avoidance type relationships). After successfully building and verifying the CODA model, the mappings between the ECs and customer needs are frozen and the model becomes a scalar function of N ECs that calculates the overall design merit (ODM) on a normalized scale from zero to unity (Eres et al., 2014) that corresponds to a total dissatisfaction and to an absolute success, respectively.

The primary design concept without avoidance function does not allow excluding such frequency ratios with the expansions that may lead to resonant vibrations. For example, the length of the span of the pipeline directly affects the natural frequency. The CODA model (see Figure 5) without the avoidance function shows a smooth dependence ODM on the span length without excluding any frequency ratios (see Figure 6).

				Customer Needs (CNs)					
		Overall Design Merit	58.39%	Easy to extend operational life	Green pipeline	Cheap to maintain and repair	Low capital expenditures (CAPEX)	Low operating expenditures (OPEX)	High earnings before interest, taxes, depreciation and amortization (EBIDTA)
			Normalised weights	15%	25%	15%	10%	15%	20%
Engineering Characteristics (Ecs)									
High strength pipes (Yield strength, MPa)			Correlation	0.9	0.9	0.9	0.3	0.3	
	Value	448	Relationship Type	Opt	Max	Min	Max	Min	
	Low Limit	250	Neutral or optimum point	400	300	448	300	550	
	Upper Limit	690	Tolerance	100					
			Merit value	81%	64%	50%	64%	57%	0%
High-grade corrosion-resistant steel pipes (Corrosion rate, MPY)			Correlation	0.3	0.9		0.9	0.3	0.3
	Value	2	Relationship Type	Max	Max		Max	Min	Max
	Low Limit	0.5	Neutral or optimum point	1	1		0.7	2	2
	Upper Limit	5	Tolerance						1
			Merit value	75%	75%	0%	86%	50%	50%
Full gas pipeline capacity (billion cubic meters per year)			Correlation	0.3	0.9	0.3		0.9	0.9
	Value	13	Relationship Type	Min	Min	Min		Max	Max
	Low Limit	6.0	Neutral or optimum point	9	9	13		7	7
	Upper Limit	16	Tolerance						
			Merit value	38%	38%	50%	0%	72%	72%
Span length (m)			Correlation	0.3	0.9	0.9	0.9	0.3	
	Value	5	Relationship Type	Max	Min	Max	Max	Max	
	Low Limit	2	Neutral or optimum point	3	7	3	3	5	
	Upper Limit	20	Tolerance						
			Merit value	69%	62%	69%	69%	50%	0%

Figure 5. The CODA model without the proposed avoidance function.

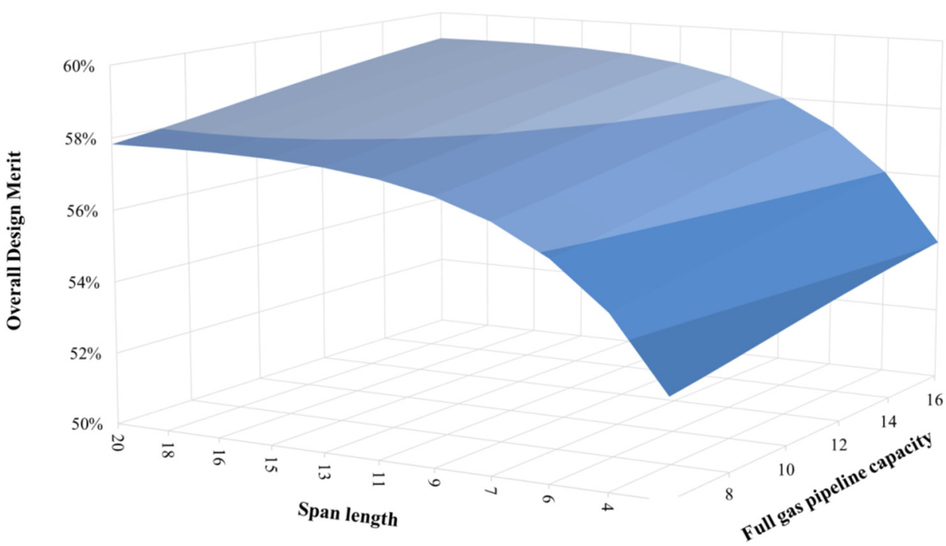

Figure 6. Overall design merit versus span length and full gas pipeline capacity for yield strength of 448 MPa and corrosion rate of 2 MPY without the avoidance function.

Such a CODA model clearly does not show that some of the magnitudes of the EC "Span length" can lead to resonant vibrations and catastrophic failures. However, if the customers require excluding or avoiding the value frequency ratio from 0.9 to 1.1, the proposed avoidance function with neutral point of 1 and tolerance of 0.1 can be used. The resulting design landscape for this CODA model is shown in Figure 7.

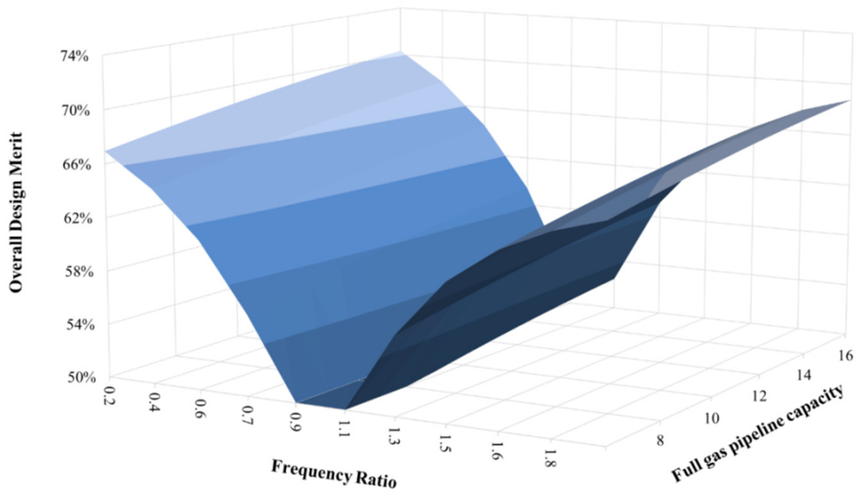

Figure 7. Overall design merit versus frequency ratio and full gas pipeline capacity for yield strength of 448 MPa and corrosion rate of 2 MPY with avoidance function in accordance to equation (3).

If the customers require extend range avoiding the value frequency ratio in accordance to formula (2), the proposed avoidance function with neutral point of 1 and tolerance of 0.7 can be used. The resultant design landscape of this CODA model with avoidance function and extended range avoiding in accordance to equation (2) is shown in Figure 8.

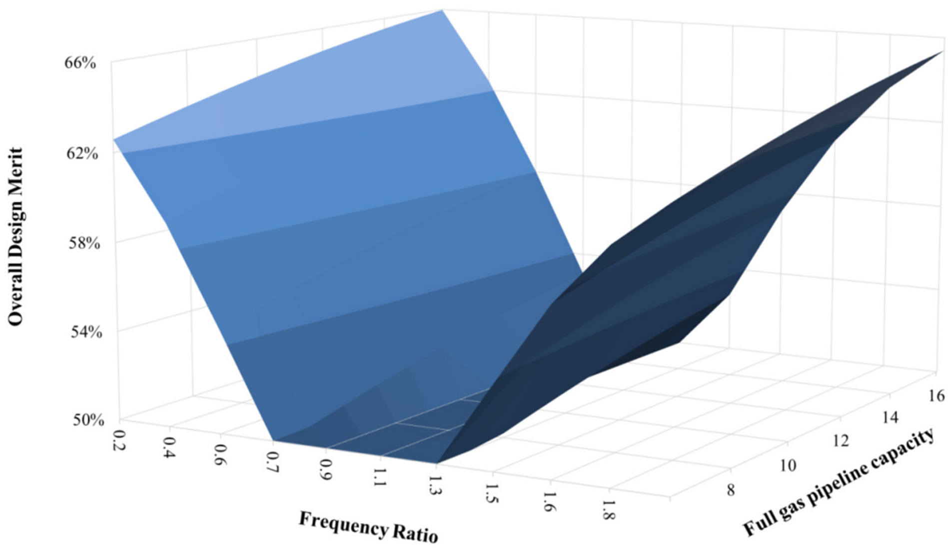

Figure 8. Overall design merit versus frequency ratio and full gas pipeline capacity for yield strength of 448 MPa and corrosion rate of 2 MPY with avoidance function and extended range avoiding in accordance to equation (2).

Frequency ratio depends upon many other engineering characteristics, so here we do not have such a degree of freedom, as if they were independent. For example, a variation of the pipe diameter or span length changes the frequency ratio by changing the natural frequencies. This problem needs a full-scale optimisation that dynamically calculates the frequency. However, this is beyond the scope of this paper.

5 DISCUSSION AND CONCLUSIONS

There is an increasing level of awareness and interest in value assessment as being an integral part of SE practices in the aerospace industry. Qualitative value assessment models represent a step forward in terms of a more robust approach to capture, consolidate, and prioritise external and internal stakeholder needs and to link them to the product's ECs. The proposed case study shows the use of the CODA approach in this respect, and exemplifies the strength of this kind of modelling for pipeline design analysis studies.

This paper also proposes improvements to the existing set of CODA functions, in order to model exclusion zones – in this case for the frequency ratio. Design standards of oil and gas pipelines require the exclusion or avoidance of some of the values or ranges of values of the natural frequencies of pipeline spans. In some cases, an overlap of natural frequencies with the forcing frequencies under variations in the rate of rotation of the compressor shaft can be achieved. The proximity to the natural frequencies of forced frequencies can lead to resonant vibrations of pipelines, damage and catastrophic failures. This overlap indicated that the frequency ratio must be yet another EC in the CODA method for the pipeline design. Hence, the introduction of the avoidance function was necessary to account for intolerable values of frequency ratio in the CODA model.

In the end, using the CODA method design teams can better identify the most important dimension to prioritise from the beginning of the design activity, and thereby reduce corrective rework in later design phases. Future work will focus on demonstrating a fully integrated optimisation workflow where the overall design merit of the pipeline CODA model will be utilised as the single objective of the optimisation.

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