Development of dynamic submarine MV power cable design solutions for floating offshore renewable energy applications

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ABSTRACT

This paper reviews approaches to design, modelling and testing of submarine dynamic power cables given the systems requirements for floating offshore renewable energy (ORE). It mainly focuses on the global loading regime and internal mechanical stress estimation in highly dynamic working conditions as well as the assessment of cable mechanical properties, strength and fatigue life.

KEYWORDS

Power cable, highly dynamic, subsea, offshore, renewable energy, fatigue life, global loads, stress distribution

INTRODUCTION

Floating offshore renewable energy (ORE) can potentially provide a significant share of the future energy generation mix. Floating foundations greatly expand offshore wind turbine deployment areas by overcoming water depth constraints. Additionally, they open up opportunities for changes to manufacturing and deployment practices that may deliver significant cost reductions. Few full size floating wind turbine prototypes have been installed with more deployments announced [1]. Developers of both wave and tidal energy converters are also deploying an increasing number of floating prototypes [2].
Most floating ORE connections to the power grid require dynamic inter-array submarine power cables. These cables must continuously withstand dynamic mechanical loading regimes during their lifetime.

Devices are typically deployed in high environmental energy density locations and must withstand full year-round environmental conditions for the project lifetime of typically over 20 years. Most technologies are designed to work in relatively shallow water (i.e. up to few hundred metres), some to respond to wave motion in highly dynamic fashion. Consequently, dynamic power cables between floating hosts and the seabed lie mostly in the wave zone and are subjected to very severe loading regimes. These power cables must be designed to operate in highly dynamic conditions with cyclical axial loading sequences and continuous bending cycles due to both environmental loads and the relative motion of the device system components.

Failures risks include tensile failures, buckling due to extreme axial loads sequences, as well as bending failure due to extreme bending loads and related cable deformation below the specified minimum bending radius. Torque balance and cross-section stress balance are fundamental requirements for any dynamic cable. However, dynamic cables for floating ORE applications are expected to require special care and full assessment of their dynamic behaviour in operation as they are subjected to a loading regime where the potential for hockling and kinking is significantly amplified.

Inherent compliance together with typical internal components arrangement and geometry make dynamic cables especially vulnerable to alternating bending loads where radially compressed layers/elements are subjected to relative motion resulting in significant risk of wear, deformation and the degradation of physical properties.

Continuous dynamic cyclic loading during operation also exposes these cables to high risk of fatigue failure. Thies et al [3] assess the global loading regime and fatigue failure modes for a submarine cable connected to wave energy converter. Nasution et al [4, 5] investigate fatigue life of stranded copper conductors subjected to severe combined tensile and bending loads.

A research project was carried out with the objective of identifying suitable design solutions for power cables in highly dynamic operating conditions in order to ensuring safe, reliable and cost effective electrical connections for floating ORE. This involved reviewing and strengthening the hydrodynamic and mechanical modelling methodology applied in dynamic cable design. A highly dynamic test cable was then designed and manufactured applying both best practices and novel solutions. Finally, the cable performance was thoroughly assessed through comprehensive mechanical testing and analysis.

METHODOLOGY

Present submarine cables design and manufacturing practices rely on a combination of theoretical and empirical models selected and developed through years of experience. A number of specialist finite element analysis (FEA) software applications are used for loads/stress analysis and design optimization.
However, uncertainties still remain regarding the precise characterisation of stresses and strains acting within a cable structure and their effects. From a structural mechanics prospective, submarine cable can be seen as an assembly of both metallic and polymeric elements with significantly different geometries and material properties. The widely dissimilar deformation responses to loading for the different elements, the effects of the interaction between adjacent components as produced by friction and stick-slip regimes on stress distribution and the impact on the individual elements material surface finish and overall mechanical properties of minimal changes in the manufacturing process are only a few of the substantial challenges to accurately model loads and related effects through numerical analysis.

Given these uncertainties, a cautious approach to design and modelling was applied throughout the project. Best practice design and manufacturing methodologies were critically reviewed and assessed together with relevant documentation – although specific submarine dynamic cable standards have not yet been issued – including ISO 13628-5 [6], DNV-RP-F401 [7] and CIGRE Electra No.171 recommendations [8]. All important design decisions were supported by numerical simulation and calibrated through physical testing. The overall iterative approach is shown in Figure 1 and is briefly explained in the following paragraph

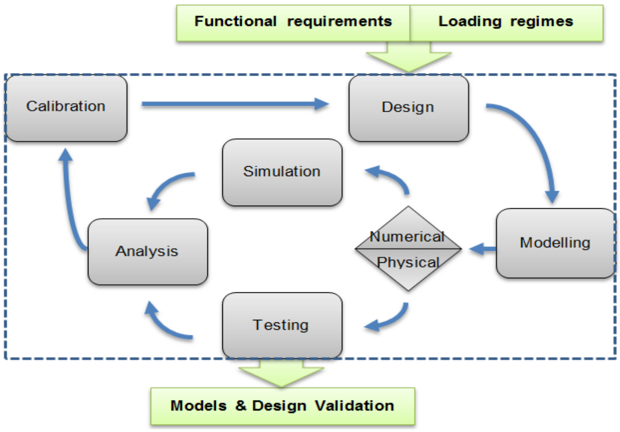

Figure 1: Methodological approach

The project started with the consolidation of significant amount of information collected on floating ORE through contacts with developers as well as literature. This included functional requirements for dynamic power cables and related accessories as well as information about hydrodynamic behaviour and loads.

Comparing and contrasting numerical and experimental results allowed the optimization and validation of design and manufacturing choices. The test program involved identifying and applying appropriate measurement and monitoring techniques aimed at assessing and validating design and modelling assumptions. A selection of cable samples and associated components were subjected to both extreme and cyclic loading regimes. A specific focus was on the assessment of fatigue failure modes and fatigue life estimation methods and included a combination of standard methods, novel test configurations and detailed component and materials analysis.

Results and analysis from both modelling and testing activities informed the design of a test cable that was manufactured and then subjected to a further cycle of accelerated testing.

The following sections present further details regarding the design activities in form of modelling and physical testing, presentation of results and conclusion.

MODELLING

A detailed understanding of both the hydrodynamic loading and internal mechanics of subsea cables is required in order to design and manufacture a cost-effective yet robust and reliable product.

Global hydrodynamic loads are the result of the combined action of direct environmental loads acting on the submarine cable together with secondary loads transferred to the cable by the motion of the floating structure due to wave, currents and wind.

In order to estimate the global load impact on the cable structure, all combinations of axial, bending and torsional loads must be converted into stresses acting locally on each cable component. This informs the calculation of the structural strength of each cable component as well as the assessment of risk of failure/damage due to extreme as well as cyclic loads.

Hydrodynamic modelling

Numerical modelling of cable dynamics and global loads estimation was carried out using OrcaFlex, finite element analysis software developed by Orcina Ltd. [9]. The application allows modelling power cable responses as well as investigating coupling effects between the cable and the floating host and/or the mooring system.

Simulations were carried out for a selection of devices representative of different energy extraction technologies and mooring configurations. The analysis included all main floating wind turbines foundation designs, namely: spar, semisubmersible and TLP as well as three floating wave energy converter types: an attenuator, a point absorber and an oscillating water column. In each case, the environmental conditions and loading of the deployment sites were applied and cable mechanical properties, accessories selection and deployment arrangement were adapted to suit the system requirements.

It should be noted that it was not always possible to run simulations with dynamic behaviour fully defined by response amplitude operators (RAO) for all investigated configurations. In those cases, system configurations were defined through given information on devices mass distribution, displacement and mooring arrangements. Consequently, effects due to power take off activity or, if applicable, motion control systems were explicitly excluded. In all cases, time-domain analysis was carried out in order to ensure the inclusion of non-linear coupling and structural effects as well as system responses to time varying currents and waves.

The activity allowed the definition of a global loading regime envelope covering a wide range of floating ORE devices. This covered both extreme and cyclic loading in the axial direction, in bending and shear. Through the analysis of dynamic behaviour and loads distribution along the cable route, critical cable sections subjected to more intense loading in operation and hence requiring special attention were also identified.

Mechanical modelling

The *von Mises stress* represents the maximum effective stress produced by the combination of tensile, compression, bending and shear loading [10]. For the present analysis the *von Mises stress* acting on each point of the individual components has been derived from the global load modelling. It is calculated by applying a combined approach of FEA modelling and cable structural analysis. Failure mode and effect analysis (FMEA) assessment can then be directly applied to confirm that all cable components can reliably operate under expected range of extreme environmental loads and hence validate the design.

Fatigue life estimation

Fatigue life modelling and estimation is a more complex process. During the expected lifetime of 20 or more years, dynamic power cables would see a whole variety of site dependent environmental conditions, ranging from violent storms to very calm sea states. The design challenge is to apply an efficient, but sufficiently reliable method to account for lifetime accumulated loading effects to ensure that the cable design life meets the specification requirement. A widely established method involves analysing metocean data for a given deployment site to generate the environmental load spectrum for the required period based on the probability of the occurrence of given sea states, current and wind. Global loads are then converted into internal stresses whose effects on fatigue life are subsequently evaluated with the use of S-N curves and *Miner-Palmgren* summation of fatigue damage principles [11]. A safety factor is then applied to account for uncertainties and simplifications.

In this project, the method is applied as follows:
A significant number of representative load states combinations are selected and hydrodynamic modelling carried out so that in each case the related cable *short-term* global loading time history can be extracted. *Von Mises stresses* are then calculated by applying the same principles described above for extreme loading assessments. In this case, however, analysis is carried out in the time-domain rather than for an individual event. Consequently, loads to effective stress calculation are more efficiently managed through conversion functions that account for the contributions of acting global axial, bending and torsional environmental loads combinations and produces effective stress time series for the affected cable components.

The conversion functions can be conveniently simplified by limiting their range of validity within a pre-defined minimum that is, loads magnitudes below which further global loads variations result in very marginal changes contribution to effective stress, and maximum loads that must not be exceeded as likely to cause failures.

Within the restricted ranges, it is normally possible to define linear conversion relations linking to a good approximation inner cable components maximum effective stress (σ_{MES}) to both curvatures (ρ) and axial load (T) as follows:

$$\sigma_{MES}[MPa] = A \times \rho[m^{-1}] + B \times T\ [kN] \qquad (1)$$

Where both *A* and *B* are coefficients that need to be calculated for each component.

The *short-term* time histories of *Von Mises* stress calculated with equation (1) can then be filtered through the *Rainflow counting algorithm* in order to convert the irregular varying stresses into simple stress reversal cycles. Additionally, the *Goodman relation* (2) is applied to calculate fatigue limit of the material σ_{fat} when subjected to alternating stress – or endurance limit for materials that do not have fatigue limit (e.g. copper) –as function of both stress amplitude σ_a and related mean stress σ_m produced by Rainflow counting. This is required in order to ensure consistency when applying S-N curves that are normally produced by subjecting test pieces to alternating stress regimes with mean stress $\sigma_m = 0$

$$\sigma_{fat} = \frac{\sigma_a}{1 - \left(\frac{\sigma_m}{\sigma_{uts}}\right)} \qquad (2)$$

Where σ_{uts} is the material ultimate tensile strength.

Any S-N curve can be described by a modified Basquin's equation as in the form

$$N = a_D \times \Delta\sigma^{-m} \qquad (3)$$

Where N and $\Delta\sigma$ are, respectively, number of cycles and stress range (that is, $2 \times \sigma_a$), while a_D and m are parameters given for the component/material.

The *Miner-Palmgren* rule of damage accumulation can then be applied to calculate the approximate damage produced by each of the k *short-time* periods.

$$D_{short\_time_k} = \sum_i \left(\frac{n_i}{N_i}\right) \qquad (4)$$

Where:

N_i is the number of cycles to failure at constant stress range as extracted from the relevant S-N curve and

n_i is the number of alternating stress cycles at the i stress amplitude in the *short-term* period.

The total estimated *long-term* fatigue damage and consequently the cable theoretical fatigue life can then be produced as collation of all the k *short-term* damages according to the probability of load states occurrences in the required period. The final critical step is the appropriate definition and application of safety factors to determine the cable design life.

The fatigue life estimation method described above has the advantage of allowing efficient handling of large amounts of data. However, it carries uncertainties and explicitly introduces major simplifications to the actually occurring physical processes. Extensive tests and measurements are essential to minimize uncertainties, calibrate the design procedure and determine the suitable safety factors that may be applied to each component and eventually the whole cable design. An overview of the project test plan is in the following section.

TESTING

The test plan included a range of both static and dynamic mechanical tests. In the initial part of the project, experimental data was required to support the progressive development and calibration of the methodology used for the estimation of dynamic cables mechanical properties. Additionally, accelerated stress testing – where loads conditions exceeding normal operations are applied in order to accelerate components degradation and the development of failures – informed and validated fatigue related failure modes and effect analysis (FMEA) assumptions as well as the suitability of specific design choices.

In the latest part of the project, the full set of tests was carried out on a newly designed highly dynamic test cable in order to reassess and validate both modelling practices and design choices. Accelerated life testing focused on components reliability and fatigue life estimation.

Static tests and related aims are summarized in Table 1.

The procedures followed established practices as described by Electra No.171 and ISO 13628-5 [6, 8].

Static mechanical tests	
Test type	**Aims**
Bend stiffness	Measurement of cables inherent stiffness. Mechanical models validation
Tensile	Measurement of both axial and torsional stiffness. Verification of components strength. Mechanical models validation

Table 1: Summary of static mechanical tests

Table 2 shows a summary of the dynamic mechanical test activities and the related aims. Overall number of cycles applied at different curvature and axial loading combinations exceeded 2.5 million cycles.

Dynamic mechanical tests	
Test type	**Aims**
Power cores Bend vs. template (PC-BaT)	Component level accelerated stress testing. Development of failure modes and effects analysis. Design choices verification.
Full cable bend vs. template (FC-BaT)	Full cable level accelerated stress testing for FMEA and design choices verification
Fully dynamic pitch, roll and heave combined loading (DMaC)	Accelerated life testing for reliability and fatigue life assessment

Table 2: Summary of dynamic mechanical tests

Electrical measurements were carried out both before and after dynamic loading on a selection of samples according to IEC 60502-2 [12] in order to confirm compliance to cable standards acceptance criteria as well as assessing possible performance degradation. All samples were dissected and visually inspected to verify type, magnitude and location of any damage/failure caused by the dynamic loading on each cable component. A further detailed analysis was carried out in material testing laboratory also assessing material properties changes produced by the loading regimes.

Further details on dynamic test procedures are presented here below.

Bending against template: PC BaT and FC-BaT

The test method involved subjecting the specimens to cyclic bending against a shaped template to apply a specific curvature. In some of the test settings, a constant axial load was also applied. The procedure followed DNV-RP-F401 guidelines [7]. One test arrangement example is shown in Figure 2.

The test plan included both *FC-BaT* tests carried out on full cable samples in order to fully assess components interactions effects within the cable structure and *PC-BaT* individual power cores test for a more focused analysis of both screen and conductor fatigue performance.

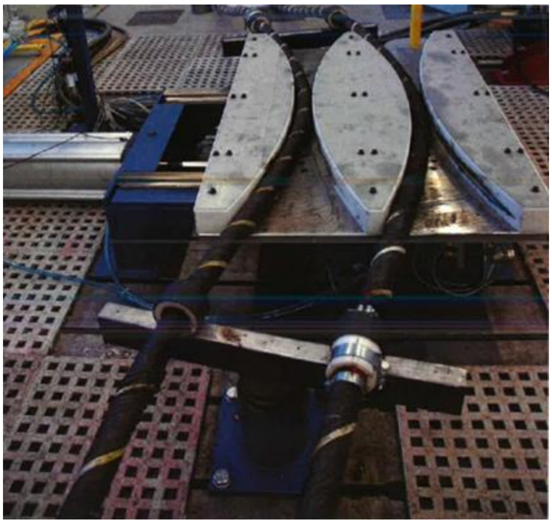

Figure 2: Bending against template test arrangement

DMaC low cycles fatigue test

The Dynamic Marine Components test facility (DMaC) is a purpose built test rig where specimens can be subjected to a loading regime that closely replicate forces and motions of the offshore environment in controlled laboratory conditions. At one end of the test rig, a linear hydraulic cylinder can apply tension and compression force (replicating heave), while at the other end the headstock can move with two degrees of freedom (replicating pitch and roll). The test arrangement is shown in Figure 3, a detailed test rig description is given in [13].

Figure 3: DMaC test arrangement

Four dynamic cable samples were tested on the DMaC test facility as part of this project. In all cases, the applied loading regimes were based on the results of *OrcaFlex* simulations that included submarine power cable with the specimens' mechanical properties. The section along the cable route subjected to the highest load was identified and the relative curvature and axial loading time series extracted to be used as DMaC input.

The procedure ensures that the loading regime applied to the sample closely reflects the full spectrum of combined axial and bending variable loading acting in offshore field deployments. At the same time, DMaC loads time series can also be adapted according to the test objectives, e.g. reaching the calculated sample fatigue life when applying the *accelerated stress testing* approach.

RESULTS

Main project results include the definition of loading regimes envelops for dynamic power cables connected to a range of floating ORE devices, the assessment of failure modes occurring under this highly dynamic operating regime together with their effects on cable functionality and safety and the implementation and validation through testing of suitable design and manufacturing solutions optimized for floating ORE operations.

The rest of this section provides a brief, mainly qualitative summary of each of the results areas. In each section, one aspect is also selected for a more detailed description.

Global loading regimes notes

In all configurations investigated as part of this project, the tensile load was never found to be a critical loading regime as its magnitude never exceeded 100 kN. On the other hand, axial compression loads were significant in some of the configurations posing some risks of buckling and/or birdcaging. In all cases suitable route configuration together with cable structural strengthening with anti-buckling tape was estimated to ensure safe and reliable operations.

Extreme bending and/or fatigue damage due to cyclic bending loads was a significant issue in all configurations. In all cases it was the governing design factor for dynamic cable, cable protection systems and cable route configuration in the water-column.

The relation between cable mechanical properties and global hydrodynamic loading was also investigated. Comparing the behaviour of cables with significantly different mechanical properties confirmed that responses to acting forces and, consequently, cable global loads in dynamic regimes are significantly dependent to cable mechanical properties. An example is shown by comparing two cables, identified as CX2 and CX3, subjected to the same environmental loading regime. The cables have identical functional specification as well as route configuration, but significantly different structural properties as shown in Table 3.

	EA	EI	Mass/OD
CX3/CX2 ratios	2.3	9.2	1.4

Table 3: CX2 vs. CX3 key mechanical differences

Figure 4 compares: a) maximum axial load and b) maximum curvature as calculated along the two cables lengths. The plots indicate that in the given configuration and operating mode, maximum tensile and bending loads acting on CX3 are, respectively, about 30% and 50% lower than on CX2.

In other words, cable design can potentially contribute to actively reduce and not only to withstand global loads. Clearly the impact on an actual implementation where cable responses need to be optimized for the whole spectrum of environmental loading in operation cannot be as significant as shown in this example. Its contribution may however be significant in highly dynamic implementations.

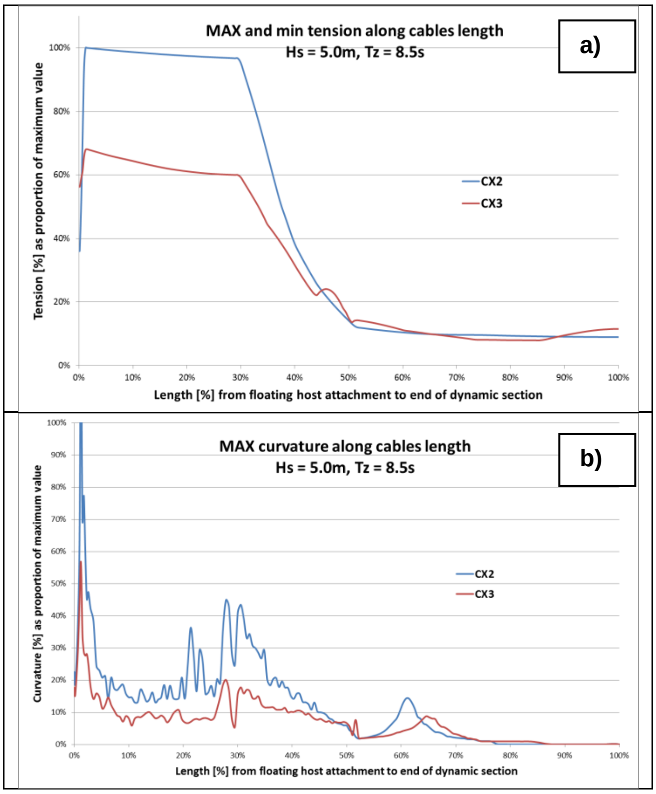

Figure 4: Structural properties effects on global loads

Fatigue life estimation and failure modes

During the physical tests full-scale cable specimens were subjected to the number of load cycles – both on the FC-BaT and DMaC test rigs – equivalent to the estimated fatigue limit. In all cases, the following cable dissection revealed damage distribution on both functional and structural components mostly in line with expectations. On the other hand, only partial or minimal degradation of the components functionality was measured. The results confirmed the understanding of failure mechanisms under dynamic load and informed the selection of design solutions included in the highly dynamic test cable aimed at minimizing components degradation due to frictional effects under a highly dynamic loading regime.

Fatigue failure in metals starts with the formation of cracks on the components surface. Fretting is one of the crack initiation mechanisms identified in copper wires conductors. It occurs at the contact area of two metallic bodies under load subjected to very small amplitude relative motion [10]. Matching oxide dark patches are normally seen on the copper wires contact points between layers when inspecting conductors subjected to cyclic loading. The thickness of oxide layer was found to increase in the section subjected to higher bending loads causing pitting on the wires surface and brittle debris flaking off.

Figure 5 shows the fretting fatigue failure of a conductor copper wire. The arrows marked with A indicate a relatively deep pitting developed at one of the contact points under the oxidized layer from where the fatigue crack propagated. It can also be noted that the adjacent point of contact, marked by the B arrow, presents a larger plastic deformation due to conductor compacting, but no sign of cracks under the oxidized layer.

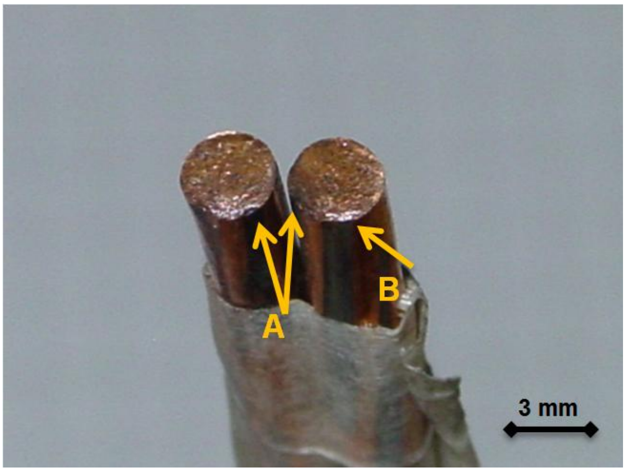

Figure 5: Fatigue failure of a copper conductor wire

Mechanical design notes

Although the description of specific mechanical design solutions is not the subject of this paper, some general notes are added here below for completeness.

The specification of the basic functional requirements for the highly dynamic test cable are shown in Table 4

Nominal voltage	12/20(24)kV
Conductors	3x 50 mm^2
FO element	6x SM + 6x MM (*)
Minimum standards applied	IEC 60840; IEC 60502-2

(*) SM = Single Mode; MM = Multi Mode

Table 4: Test cable basic functional requirements

The cases investigated throughout this project presented a variety of functional specifications and loading regimes demanding slightly different dynamic cable design solutions. It is noteworthy that in all cases fatigue was found to be the governing failure mode.

Maximizing cable fatigue life was a key project design objective. Design solutions and manufacturing practices minimizing stress distribution within cable structure under dynamic loading regimes were tested, selected, implemented in a specially designed test cable and finally validated. They can be summarized with two general principles:

- Optimal components stress balance - where the near totality of loads are carried by cable components included for strength and protection - must be ensured in all global loading operating conditions in order to prevent mechanical overloading of the cable functional elements including conductors, insulation systems, metallic screens and fiber optics.
- Decoupling of the structural metallic and polymeric strength elements from the functional components must be maximized to ensure both good stress distribution in bending and easily slip in all operating load conditions. This then minimizes materials degradation due to friction effects.

The cable bend and axial stiffness, as well as its mass/volume ratio may be also optimized in order to minimize the cable responses to both direct and secondary loading.

CONCLUSION

The project enabled to further strengthen capabilities in modelling, design and testing of dynamic submarine power cables. Specific solutions addressing floating ORE systems requirements were implemented in a specially designed and manufactured test cable. An extensive test program was carried out to validate design solutions and confirm cable reliability.

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