

**Bakhtmutskaya Ju. O., Goloshchapov V. N. K-325-23,5 Steam Turbine High-Pressure Rotor Thermal and Thermo-structural State during cold start-up.....3–11**

*The high-pressure turbine rotor is the most critical and costly steam turbine component. Service experience for the machines with a power of 150 MW and more shows that cracks appear in the region of regulation stage fillets and end seals in high-pressure turbine rotors. The cause of this effect can be the high thermal gradients during turbine pre-start and cold start-up. For steam turbine components, the thermal state is strongly influenced by the condensation process, which takes place during the turbine pre-start and cold start-up phase. The process continues until the rotor surface temperature becomes higher than the steam saturation temperature. Condensation heat transfer coefficients are much higher than that of calculated for the case without condensation. In this article to simulate the rotor heating process during turbine pre-start with the highest accuracy, several aspects are studied. Steam characteristics in rotor flow path and end seals regions were determined for K-325-23,5 turbine taking into the account leakages through drainages and specificity of turbine heating through exhaust hood. To determine steam parameters in front end seals chamber, which is connected to the inter-casing space, the condensation process duration in at cold start-up was determined. Thermal conditions were calculated taking into the account the condensation effect. K-325-23,5 turbine pre-start and cold start-up technology was analyzed with regards to high-pressure rotor thermal and thermal stress-strain state. Thermal and thermo-structural analyses results show that significant rotor portion in the region of front end seal stays cold for the whole period from vacuum set up to acceleration phase. Such non-rational heating at the prestart phase leads to significant thermal gradients and thermal stresses which are above the material yield strength. As a result of the study, the design improvement is suggested which consists of additional chambers arrangement in front end seals carrier along with additional steam flow organization at the prestart phase. Such improvements allows to: 1) provide high-pressure rotor uniform heating in the front end seal region; 2) increase turbine reliability due to decreased level of thermo-stresses.*

**Keywords:** steam turbine, high pressure rotor, boundary conditions, thermal state, thermal stress.

*Выполнено расчетное исследование теплового и термонапряженного состояний ротора цилиндра высокого давления паровой турбины ПАО «Турбоатом» мощностью 325 МВт на этапах прогрева и пуска турбины из холодного состояния. Для определения нестационарного теплового состояния ротора получены тепловые граничные условия 3-го рода. Учитывался процесс конденсации пара на поверхностях элементов ротора и межкорпусного пространства. Предложено изменение конструкции и условий прогрева ротора высокого давления в области переднего концевое уплотнения на этапе подготовки к пуску из холодного состояния и показана возможность снижения уровня термических напряжений, возникающих при пуске турбины.*

**Ключевые слова:** паровая турбина, ротор высокого давления, граничные условия, тепловое состояние, термонапряжения.

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**Shcherbakov N. S., Parafeynik V. P., Ryabov A. A., Shevchuk V. V., Raznoshynskyy V. N., Tertyshnyi I. N., Prilipko S. A.** Selection of System Characteristic of Turbo-Compressor Package Based on Efficiency Analysis according to Full-Scale Test Results. P. III. Efficiency Research of Basic Systems of Turbo-Compressor Package GPA-C-6,3A/56-1,45 on Full-Scale Test Results ..... 11–18

*The paper is concerned with design and experimental characteristics of efficiency of natural gas centrifugal compressor (CC) and driven gas turbine at different conditions obtained on the results of physical experiments conducted during full-scale tests of GPA-C-6,3A. Comparative analysis of CC design and experimental characteristics showed that it is observed the good agreement of design and experimental characteristics for compressor design condition. Data analysis showed that under CC design condition the commercial capacity 12.2 MMNCMD, pressure ratio 1.45, polytropic efficiency 85% are provided, and consumed shaft power is 6.17 MW meeting technical requirements. The paper also presents data on hydraulic pressure losses effect in air intake and exhaust ducts on useful power and efficiency of driven engine under nominal condition. Thermaltechnical characteristics were obtained upon turbine (being the part of the package) test results. Under power turbine power 6.3MW the turbine effective efficiency was 30%, and specific fuel rate was 0.24 kg/kW-h. This data as well as operation parameters of TCA being the part of back-to-back test rig is the initial data to make up system characteristics of the package to be researched.*

**Keywords:** turbo-compressor package, computational experiment, physical experiment, centrifugal compressor, gas turbine engine, compressor polytropic efficiency, turbine effective efficiency, hydraulic power loss.

*В работе представлены расчетные и экспериментальные характеристики центробежного компрессора (ЦК) природного газа и приводного газотурбинного двигателя на различных режимах их работы, полученные по результатам натурных экспериментов, проведенных в процессе испытаний агрегата типа ГПА-Ц-6,3А на стенде замкнутого контура (ЗК). Сравнительный анализ расчетных и экспериментальных характеристик ЦК показал, что для проектного режима работы компрессора наблюдается удовлетворительное совпадение характеристик. Полученные данные показали, что при расчетном режиме работы ЦК обеспечивается коммерческая производительность 12,2 млн м<sup>3</sup>/сутки, отношение давлений 1,45, политропный КПД равен 85%, а потребляемая мощность на валу компрессора составляет 6,17 МВт, что соответствует требованиям технического задания. По результатам теплотехнических испытаний двигателя в составе агрегата получены его характеристики. При мощности силовой турбины равной 6,3 МВт эффективный КПД двигателя соответствовал 30%, а удельный расход топлива 0,24 кг/кВт·ч. Получены также данные о влиянии гидравлических потерь в воздухоприемном и выхлопном трактах газотурбинного привода на полезную мощность и эффективность приводного двигателя на номинальном режиме работы. Эти данные, а также параметры работы турбокомпрессорного агрегата в составе стенда ЗК являются исходными для составления системной характеристики исследуемого агрегата и оптимизации режимов его работы при дальнейших исследованиях.*

**Ключевые слова:** турбокомпрессорный агрегат, вычислительный эксперимент, физический эксперимент, центробежный компрессор, газотурбинный двигатель, полнотронный КПД компрессора, эффективный КПД двигателя, гидравлические потери.

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**Tarelin A. A., Nechaev A. V., Hinevich A. E.** Electromagnetic radiation in the steam turbine.....18–21

*Electrization of working fluid in the wet steam turbine results in occurrence of electromagnetic radiation in the exhaust part of the turbine. The purpose of the investigation is experimental study of parameters electromagnetic radiation and discuss its influence on the efficiency and reliability of turbine. Electromagnetic radiation received by string antennas in the turbine exhaust part. Measurement of electromagnetic radiation parameters was carried out by using a spectrum analyzers. It has been found electromagnetic radiation in the form of noise from kilohertz to tens of megahertz. It was also found high frequency component near 2 GHz. Total power of the electromagnetic radiation of ionized wet steam flow in exhaust part turbine can reach several kilowatts. Proof of this can be found in the experiment damage of cables insulation laid in the turbine condenser. Another manifestation electromagnetic radiation are high frequency current induced in the electric circuit of the probe installed in the exhaust of the turbine. Results presented in the paper show that the electromagnetic radiation can affect on performance and reliability of the wet steam turbine.*

**Keywords:** steam turbines, electrization of wet steam, electric discharges, electromagnetic radiation.

*В статье представлена информация об электромагнитных излучениях в зоне выхлопа турбины, связанных с электризацией влажного пара. Приведены данные измерений электромагнитного излучения за последней ступенью турбины. Описаны эффекты влияния электромагнитных явлений на экспериментальное электротехническое оборудование, размещенное в конденсаторе турбины. Обсуждаются возможные механизмы влияния электромагнитных излучений на эффективность и надежность турбоустановки.*

**Ключевые слова:** паровые турбины, электризация влажного пара, электрические разряды, электромагнитные излучения.

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*Aerohydrodynamics and heat-mass exchange*

**Andreeva O. L., Kostikov A. O., Tkachenko V. I.** Heat convection of viscous incompressible liquid in a cylindrical elementary convection cell with a conical cavity bottom and rigid boundary conditions .....22–28

*There was studied the problem of heat convection of viscous incompressible liquid in a cylindrical elementary convection cell with a conical cavity bottom and rigid boundary conditions. For a special case there were obtained expressions of distribution for perturbed velocity and temperature in cylindrical system coordinate with rigid boundaries. It shows the diagram of a cylindrical unit cell with convective conically recessed bottom in a layer of a viscous, incompressible fluid and rigid boundary conditions. Defined spatial field distribution of flow velocities in a cell with a conically recessed bottom and rigid boundary conditions on the surface  $z = 1$  and  $z = 0$ . Top elementary convective cell borders on a horizontal array of metallic heat dissipating layer thickness, from below - from a horizontal layer heat input medium, temperature gradient is maintained constant thickness. Stokes' functions were constructed for cylindrical convection cell as well as for the conical cavity in the cell bottom. Basing on Fujiwhara effect there were obtained Stokes streamline model distributions in the cylindrical elementary convection cell with conical cavity bottom and solid boundary conditions and disturbed temperature. In this paper we consider the problem of convective heat and mass transfer in a cylindrical elementary convection cell with a conical depression heated from below.*

**Keywords:** *cylindric elementary convection cell, heat convection, conical cavity, solid boundary conditions, viscous incompressible liquid, Fujiwhara effect.*

*Рассмотрена задача о тепловой конвекции вязкой несжимаемой жидкости в цилиндрической элементарной конвективной ячейке с конически углубленным дном и твердыми граничными условиями. Построены функции Стокса в цилиндрической конвективной ячейке, а также коническом углублении дна ячейки. На основании эффекта Фудзивары получены модельные распределения линий тока Стокса в цилиндрической элементарной конвективной ячейке с конически углубленным дном и твердыми граничными условиями.*

**Ключевые слова:** *цилиндрическая элементарная ячейка, тепловая конвекция, коническое углубление, твердые граничные условия, вязкая несжимаемая жидкость, эффект Фудзивары.*

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### *Dynamics and Strength of Machines*

**Hasanov Sh. G.** Solution of contact problem for plane weakened of variable width slot in inhomogeneous stress field.....29–36

*A mathematical description of partial closure of a variable width slot in a plane in inhomogeneous stressed field is given. The weakened plane is elastic and isotropic. It is assumed that the variable width of the slot is comparable with the elastic deformations. The interaction of slot surfaces under influence of the inhomogeneous stressed field can lead to appearance of zones of surfaces contact. The contact stresses arising between the slot faces and the boundary of the contact zones are initially unknown and are found in the solution process. The occurrence of several contact zones of the slot faces is investigated. It is assumed that in the contact zone partially faces adhesion and partially faces slippage arise; and on the faces slippage zones the dry friction forces act. The problem on equilibrium of the slot with partially contacting faces reduces to the problem of linear conjugation of analytic functions. The solution of the contact problem is obtained in quadratures.*

**Keywords:** isotropic plane in inhomogeneous stress field, variable width slot, contact zones, contact stresses.

*Дается математическое описание частичного закрытия щели переменной ширины в плоскости в неоднородном напряженном поле. Ослабленная плоскость считается упругой и изотропной. Принято, что переменная ширина щели сравнима с упругими деформациями. Взаимодействие поверхностей щели под действием неоднородного напряженного поля может приводить к возникновению зон их контакта. Контактные напряжения, возникающие между берегами щели, и границы зон контакта изначально неизвестны и находятся в процессе решения. Исследуется возникновение нескольких участков контакта берегов щели. Считается, что на площадке контакта частично возникает сцепление берегов щели, частично – их проскальзывание, при этом на участках проскальзывания имеют место силы сухого трения. Задача о равновесии щели с частично контактирующими берегами сводится к задаче линейного сопряжения аналитических функций. Решение контактной задачи получено в квадратурах.*

**Ключевые слова:** изотропная площадь в неоднородном поле напряжений, щель переменной ширины, контактные зоны, контактные напряжения.

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**Polischuk O. F., Avramov K. V., Myagkohleb K. B.** Experimental analysis of forced nonlinear vibrations of beams with breathing cracks .....36–42

*The cracks are one of the most common reasons of the structure damage leading to accidents. In order to avoid these damages, it is very important to reveal the cracks in time. The aim of the research, which is treated in this paper, is experimental determination of the diagnostic criterion of the crack appearance. The formation of the breathing crack is diagnosed according to the parameters of the nonlinear vibrations, which are sensitive to the cracks breathing. The parameters of the nonlinear vibrations can be used as diagnostic criterion of the crack formation. The forced vibrations experimental data of the beams with big depth cracks are considered. The kinematic excitation of the beam is reproduced by the shaker. The data of the vibrations analysis are shown on the frequency responses. The Fourier analysis of the periodic vibrations is carried out. The vibration hysteresis is analyzed experimentally. The data of the Fourier analysis are shown on the frequency responses. The amplitudes of the first and the third harmonics of the Fourier series are shown. The quenching is indicated only for the amplitudes of the first harmonic. The amplitudes of the second and third harmonics are shown on the separated figure.*

**Keywords:** forced nonlinear vibrations, beam, crack.

*Наличие трещин является одной из наиболее распространенных причин разрушения конструкций. Для того чтобы избежать этих разрушений, проводятся исследования для разработки диагностических критериев появления трещин. Целью исследования, представленного в данной статье, является экспериментальное определение диагностических критериев появления трещин. Параметры нелинейных колебаний конструкций чрезвычайно чувствительны к образованию дышащих трещин, поэтому могут использоваться в качестве диагностических критериев при образовании трещин. Экспериментально исследуются вынужденные колебания стержней с поперечными дышащими трещинами большой глубины. Колебания стержней возбуждаются кинематическим движением заделки, которое воспроизводится с помощью вибростенда. Результаты анализа колебаний представлены на амплитудно-частотной характеристике. Анализируются Фурье спектры периодических колебаний. Исследуются области многозначности колебаний. Результаты спектрального анализа колебаний изображены на амплитудно-частотной характеристике. Представлены величины первой и третьей гармоники ряда Фурье. Срыв колебаний показан только для первой гармоники. После срыва исследуются колебания при квазистатическом уменьшении частоты возбуждения колебаний. Представлены амплитуды вторых, третьих и четвертых гармоник периодических колебаний.*

**Ключевые слова:** вынужденные нелинейные колебания, стержень, трещина.

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**Morhun S. A.** Improving the mathematical models applied for the solution of solid assembly constructions thermoelasticity problem.....42–46

*The problem of sleeve and shaft assemblies finite elements models development has been studied. All calculations have been provided for the assemblies that are widely spread in the power-plant engineering and marine engine building. The matter is that such details have constructional non-homogeneity, which hardly ever could be correctly explained, using well-known finite elements and their mathematical dependences. On the other hand, the mathematical model should be as simple as possible for the purpose of its wide usage in the process of assembly's design. That is why the new finite elements model, which consists of three-dimensional isoparametric finite elements, has been developed. It has been used for the calculation of displacement, caused by complex influence of heat flux and contact load. Such approach gives an opportunity to describe the whole assembly as the superposition of the developed sleeve and shaft finite elements models and make the process of calculation more correct and even compact. All calculations of displacement and temperature fields have been held for two widely spread conjugation types, that are used for such assemblies creation.*

**Keywords:** *three-dimensional finite elements, shaft, sleeve, fields of displacement and temperature, gap, negative allowance.*

*Изложена методика построения уточненной конечно-элементной модели сборочных конструкций типа «вал» – «втулка», имеющих значительное распространение в энергомашиностроении. С использованием разработанных трехмерных конечных элементов решена контактная термоупругая задача для данного типа соединений. Получено поле распределения перемещений на торцевых поверхностях вала и втулки, а также поле распределения температур в соединении.*

**Ключевые слова:** *трехмерные конечные элементы, вал, втулка, поля перемещений и температур, зазор, натяг.*

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**Mir-Salim-zada M. V.** Partial closure of rectilinear bridged cracks in stringer plate with a hole .....46–53

*An elastic isotropic plate reinforced by stringers and having a circular hole has been considered. From the circular hole two symmetric rectilinear bridged cracks are originate. Size of the cracks end zones (zones with the interfacial bonds) is comparable with size of the cracks. The case of partial closure of the cracks is considered. Size of the zones of the crack faces contact is unknown in advance. Effect of the stringers is replaced by unknown equivalent concentrated forces applied at the points of the ribs and plate joining. For definition of the parameters characterizing the closure of cracks, a singular integral equation has been obtained. The singular integral equation has been reduced to a finite nonlinear algebraic system using the algebraization procedure. Solving the algebraic system by the method of successive approximations, the cohesive forces in the bonds, the contact stresses and the size of the contact zones of the cracks have been found.*

**Keywords:** stringer plate, circular hole, cohesive forces in bonds, contact of crack faces, contact stresses.

*Исследуется бесконечная упругая изотропная пластина, имеющая круговое отверстие, из контура которого исходят две симметричные прямолинейные трещины. Полагается, что в зонах трещин, примыкающих к вершинам, между берегами имеют место связи (силы сцепления). Размер концевых зон трещин, где имеются связи, сравним с размером трещин. К пластине симметрично относительно ее поверхности приклепаны поперечные стрингеры. Рассмотрен случай частичного закрытия трещин в концевых зонах. Размер зон контакта берегов трещин заранее неизвестен. Действие стрингеров заменяется неизвестными эквивалентными сосредоточенными силами, приложенными в точках соединения ребер с пластиной. Для определения параметров, характеризующих закрытие трещин, получено сингулярное интегральное уравнение, которое с помощью процедуры алгебраизации сведено к конечной нелинейной алгебраической системе. Решая алгебраическую систему методом последовательных приближений, были найдены силы сцепления в связях, контактные напряжения и размер контактных зон трещин.*

**Ключевые слова:** стрингерная пластина, круговое отверстие, силы сцепления в связях, контакт берегов трещин, контактные напряжения.

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*Applied Mathematics*

**Sheiko T. I., Maksymenko-Sheiko K. V., Litvinova Yu. S., Lisin D. A.** R-functions and chevron surfaces in machine building .....54–60

*In this article, was developed methodologies and constructed equations of different heat transfer surfaces of the fins, including Chevron with the help of R-functions theory. The resulting equations of surfaces have been implemented on a 3D printer. Ribbing not only increases the heat transfer surface, but also has a great influence on the hydrodynamics of the flow, and thus on the heat transfer coefficient. In experiments with various methods of finning of Fuel rod claddings were developed more favorable shape of the fins, the so-called Chevron and multi-zone. With the Chevron ribbing the entire surface of the shell is divided into four, six or eight sectors and adjacent sectors of the spiral are located symmetrically relative to the longitudinal axis. Because of the complexity and high cost of manufacturing Chevron transmission is used less frequently than helical, i.e. only in those cases when it is required to transmit high power and high speed, and the axial load of junk. On special machines V-wheels are made all of one piece. A disadvantage of the Chevron ribbing is the high complexity and cost of manufacturing. Thanks to the technology of 3D printing, these deficiencies can be remedied, because the benefits of using 3D printers is reducing the cost of production, reduction of terms of its appearance on the market, the modeling of objects of any shape and complexity, rapidity and high precision manufacturing, the use of different materials, including concrete, hydrogel, wood, metal, plastics, chocolate and even living cells. The article examines the technology of 3D printing. The analysis of the major representation schemes of models of continuous bodies, which revealed significant shortcomings. From the point of view of universality, one of the most promising functional representation, which is based on the use of language implicit mathematical functions with the structural features of the R-functions theory, developed by academician V. L. Rvachev. The analytical description of the designed objects enables to use symbolic geometrical parameters, complicated superposition of functions consequently allowing to change the design elements of these objects. The positivity feature of the built functions in the mid points of the object is convenient to 3D-printing implementing.*

**Keywords:** R-function, mathematical model, the fins of heat transfer surfaces, Chevron.

*В данной статье на основе теории R-функций разработаны методики и построены уравнения различных теплопередающих поверхностей оробрения, в том числе шевронных. Оробрение не только увеличи-*

вает поверхность теплообмена, но и оказывает большое влияние на гидродинамику потока, а тем самым и на коэффициент теплоотдачи. Полученные уравнения поверхностей были реализованы на 3D-принтере. Шевронные колёса решают проблему осевой силы, однако ввиду сложности и высокой стоимости изготовления шевронные передачи применяют реже. Технология 3D-печати позволяет снизить себестоимость и трудоемкость изготовления продукции, в том числе шевронных колес. Аналитическая запись проектируемых объектов дает возможность использовать буквенные геометрические параметры, сложные суперпозиции функций, что, в свою очередь, позволяет оперативно изменять их конструктивные элементы. Свойство положительности построенных функций во внутренних точках объекта весьма удобно для реализации 3D-печати.

**Ключевые слова:** R-функции, математическая модель, оребрение теплопередающих поверхностей, шеврон.

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#### Materials Science in Mechanical Engineering

**Vakulenko K. V., Biblik I. V., Kazak I. B.** Complex estimation of material degradation at the cyclic loading.....61–66

*The possibility of applying a complex approach combining the results of coercimetric control with the results of computer simulation conducted within the framework of a special calculation-experimental method is based on the idea of scattering of mechanical characteristics of materials and the statistical nature of their destruction. The fatigue life of 40X steel in the initial state and after surface plastic deformation was estimated. The dependences of the fatigue damage accumulation rate obtained by the two methods are compared. It is shown that practically their complete coincidence is observed both for samples in the initial state and for surface-hardened samples. The absolute values of the rate of damage accumulation are higher for non-hardened samples. It is shown that a characteristic feature of the joint use of magnetic control of a material by coercive force and computer modeling is the possibility of revealing the initial stages of the generation of defects and preventing their development to critical dimensions. Such an approach can be relevant in connection with the transition from equipment operation "to failure" to its operation with a specified level of reliability and safety, i.e. with a "predictable resource".*

**Keywords:** computer modeling; coercive force; state of the surface; Fatigue life,

*Установлена возможность применения комплексного подхода, объединяющего результаты коэрцитивметрического контроля с результатами имитационного компьютерного моделирования, проводимого в рамках специального расчетно-экспериментального метода, в основу которого положены представления о рассеянии механических характеристик материалов и о статистической природе их разрушения, для оценки усталостной долговечности стали 40X в исходном состоянии и после поверхностного пластического деформирования. Проведено сравнение зависимостей скорости накопления усталостных повреждений, полученных двумя методами. Показано, что наблюдается практически полное их совпаде-*

ние как для образцов в исходном состоянии, так и для поверхностно упрочненных образцов. Абсолютные значения скорости накопления повреждений выше для неупрочненных образцов. Показано, что характерной особенностью совместного использования магнитного контроля материала по коэрцитивной силе и компьютерного моделирования является возможность выявления начальных стадий зарождения дефектов и предупреждения их развития до критических размеров. Такой подход может быть актуальным в связи с переходом от эксплуатации оборудования «на отказ» к работе его с заданным уровнем надежности и безопасности, т.е. с «прогнозируемым ресурсом».

**Ключевые слова:** компьютерное моделирование; коэрцитивная сила; состояние поверхности; усталостная долговечность.

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