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TABLE OF CONTENTS

VOLUME 1

ACOUSTIC IMAGING AND ACOUSTIC DETECTION

LOCALIZATION OF MULTIPLE ACOUSTIC SOURCES USING A MAXIMUM LIKELIHOOD METHOD IN THE SPHERICAL HARMONIC DOMAIN.....	1
<i>Hu Yuxiang, Lu Jing</i>	
A NOVEL TWO-STAGE SOUND FIELD IMAGING TECHNIQUE USING A FARFIELD RANDOM ARRAY	9
<i>Bai Mingsian R., Chen You Siang, Lo Yi-Yang, Chun Chung</i>	
RECONSTRUCTION OF PARTICLE VELOCITY FIELD AND SOUND PRESSURE FIELD ON THE SOURCE SURFACE BY JOINTLY UTILIZING PARTIAL SOUND PRESSURE AND NORMAL VELOCITY	17
<i>Zhao Yinglong, Zhu Haichao, Mao Rongfu, Su Changwei, Su Junbo</i>	
ERROR ANALYSIS AND EXPERIMENTAL INVESTIGATION OF THE MAPPING RELATIONSHIP BASED NAH WITH SPHERICAL SOLUTION	25
<i>Wu Haijun, Jiang Weikang</i>	
CLUSTERING INVERSE BEAMFORMING FOR VEHICLES NVH	33
<i>Colangeli Claudio, Janssens Karl, Chiariotti Paolo, Castellini Paolo</i>	
REMOTE ACOUSTIC SENSING OF BOUNDARY DEFECTS IN A PLATE IN A MULTIPATH ENVIRONMENT WITH KNOWN OR UNKNOWN INPUT FORCING	41
<i>Flynn Tyler, Dowling David</i>	
ACOUSTIC SOURCES ANALYSIS USING A VIRTUAL ARRAY BASED ON MEMS MICROPHONES	49
<i>Izquierdo Alberto, Villacorta Juan José, del-Val Lara, Suarez Luis, Suarez David</i>	
COMBINED IMAGING TECHNOLOGIES FOR DETECTION OF AIR LEAKS IN MODERN AIRTIGHT CONSTRUCTIONS	57
<i>Patil Nikhilesh, Fitton Richard, Marshall Alex, Waddington David</i>	

MEASUREMENT TECHNIQUES AND SENSORS

PRESSURE, HUMIDITY, TEMPERATURE MEASUREMENTS AND LONG-RANGE RADIO TRANSMISSION USING LAACES BALLOON	65
<i>Li Zhuang, Broussard Colby, Weber Nathan, Morgan Tyler, Gaspard Dylan, Rich Brian</i>	
STUDY AND MIMICKING THE TIME DELAY MAGNIFICATION OF THE FLY EAR.....	73
<i>Zhang Yaqiong, Yang Ming, Zhu Xinlei, Liu Ling, Ta Na, Rao Zhushi</i>	
APPLICATION OF THE LOCAL PLANE WAVE METHOD TO MEASURE IN-SITU SOUND ABSORPTION USING A SPHERICAL MICROPHONE ARRAY	81
<i>Consten Niels, de Jong Anne, Wijnant Ysbrand</i>	
DEVELOPMENT OF A TEST SYSTEM FOR VOICE MONITORING CONTACT SENSOR: PHONATORY SYSTEM SIMULATOR.....	89
<i>Casassa Federico, Troia Adriano, Schiavi Alessandro</i>	
CASE STUDY OF APPLICATION OF WIRELESS MEASUREMENT SYSTEM	97
<i>Ohya Masaharu, Kurosawa Yu, Nakajima Yasutaka</i>	
A LOW COST PLATFORM FOR NOISE MAPPING USING SMART PHONES	101
<i>Lee Heow Pueh, Garg Saurabh, Lim Kian Meng</i>	
ELIMINATING WIND NOISE CONTAMINATION OF WIND TURBINE NOISE AMPLITUDE MODULATION RATINGS	107
<i>von Hunerbein Sabine, Kendrick Paul, Kerscher Michael, Bradley Stuart</i>	
DETERMINATION OF THE UNCERTAINTY CONTRIBUTION OF ACOUSTIC FRONT ENDS ON SOUND PRESSURE LEVEL MEASUREMENTS	114
<i>Wu Lixue</i>	
COMPARISON OF THE METHODS TO CALIBRATE THE DIFFUSE FIELD SENSITIVITY OF LABORATORY STANDARD MICROPHONE	122
<i>Cho Wan-Ho, Kwon Hyu-Sang, Chang Ji-Ho</i>	
ACOUSTIC PROPERTIES TEST OF MATERIALS BY THE DUAL-MICROPHONES BROADBAND IMPULSE METHOD	128
<i>Hou Hong, Huang Yunke, Yang Jianhua</i>	
IN-SITU MEASUREMENT OF TRANSMISSION LOSS USING THE LOCAL PLANE WAVE METHOD	136
<i>Wijnant Ysbrand</i>	
A ROBUST DIRECTION OF ARRIVAL ESTIMATION ALGORITHM FOR PLANAR ARRAYS TO DETECT COHERENT SOURCES IN NOISY ENVIRONMENT.....	144
<i>Singh Arun Prakash, Tiwari Nachiketa</i>	
NEW EFFECTS OF ONE-POINT MECHANICAL METAL-TO-METAL CONTACT ALLOWING THE MEASUREMENT OF HIGH FREQUENCY VIBRATION USING HANDHELD PROBES AND HEAVY VIBRATION SENSORS.....	152
<i>Zusman George</i>	

MODAL SHAPE MEASUREMENT OF LARGE INDUSTRIAL COMPONENTS EMPLOYING FRINGE PROJECTION WITH 2D-DIC	160
<i>Felipe-Sesé Luis, Patterson Eann, Díaz-Garrido Francisco</i>	
FULL-FIELD MODAL IDENTIFICATION FROM EXPERIMENTAL TRANSMISSIBILITY FUNCTIONS	168
<i>Molina-Viedma Ángel Jesús, López-Alba Elías, Díaz Francisco</i>	
LOW FREQUENCY HIGHLY DIRECTIONAL AIR COUPLED ULTRASOUND SENSOR.....	176
<i>Legg Mathew, Bradley Stuart</i>	
ON-ORBIT PERFORMANCE ANALYSIS OF ULTRASONIC FLOW MEASUREMENT	184
<i>Chen Yong, Gan Xiaohua, Chen Xiaoqian, Huang Yiyong, Yuan Bo</i>	

LOCATION AND FOCUSING

HIGH RESOLUTION BEAMFORMING USING COMPRESSIVE SENSING	192
<i>Xu Zhongming, Song Shaoyu, He Yansong, Zhang Zhifei</i>	
THE EXPERIMENTAL RESULTS OF DOUBLE NEARFIELD ACOUSTIC HOLOGRAPHY METHOD FOR MIDDLE FREQUENCY SOUND SOURCES	200
<i>Nagamatsu Masao</i>	
A ROBUST IDENTIFICATION AND LOCALIZATION METHOD OF NOISE SOURCE USING SECOND ORDER CONE PROGRAMMING (SOCP) AND NEARFIELD AMPLITUDE COMPENSATION	208
<i>Zhou Sitong, Shuai Changgeng, Wu JiaoYang</i>	
APPLICATION OF PLANAR MICROPHONE ARRAYS AND COMPRESSIVE SENSING FOR LOCALIZATION OF COMPRESSED AIR LEAKAGES	214
<i>Ning Fangli, Zhang Chao, Liu Yong, Wei Juan</i>	
THE ITERATIVE ALGORITHM USED FOR THE PHASE CONJUGATION METHOD TO IMPROVE THE SOUND SOURCE RESOLUTION	221
<i>Liu Song, Li Mao Fa, Li Sheng</i>	

ANALYSIS, PERCEPTION AND RENDER OF 3D SPATIAL SOUND

LONG-TERM USER ADAPTATION TO AN AUDIO AUGMENTED REALITY SYSTEM	229
<i>Engel Juan Isaac, Picinali Lorenzo</i>	
3D AUDIO AR/VR CAPTURE AND REPRODUCTION SETUP FOR AURALIZATION OF SOUNDSCAPES	237
<i>Gupta Rishabh, Lam Bhan, Hong Jooyoung, Ong Zhen Ting, Gan Woon-Seng, Chong Shyh Hao, Feng Jing</i>	
MICROPHONE ARRAY DESIGN FOR SPATIAL AUDIO OBJECT EARLY REFLECTION PARAMETRISATION FROM ROOM IMPULSE RESPONSES.....	242
<i>Galindo Miguel Blanco, Jackson Philip J.B., Coleman Philip, Remaggi Luca</i>	
PLANARITY ANALYSIS OF ROOM ACOUSTICS FOR OBJECT-BASED REVERBERATION	250
<i>Coleman Philip, Jackson Philip J.B.</i>	

MEASUREMENT UNCERTAINTY IN ACOUSTICS

SELECTION OF MICROPHONE LOCATION, MEASUREMENT UNCERTAINTY AND CALCULATED NOISE MAPS	258
<i>Montes-González David, Barrigón-Morillas Juan-Miguel, Godinho Luis, Amado-Mendes Paulo, Rey-Gozalo Guillermo, Atanasio-Moraga Pedro</i>	

INSTRUMENTATION FOR SOUND VIBRATION MEASUREMENTS AND ANALYSES

A TEST BENCH ENHANCEMENT FOR PUMP VIBROACOUSTIC RESEARCH	266
<i>Rekadze Pavel, Rodionov Leonid</i>	
STEREOSCOPIC OPTICAL MEASUREMENT OF TRANSVERSE VIBRATIONS IN THE ANCIENT ART OF WAYANG KULIT.....	274
<i>Kusumaningtyas Indraswari, Parikesit Gea O.F.</i>	
FAR FIELD SOUND PRESSURE FROM HIGH SPEED VIDEO FOOTAGE.....	280
<i>Lamb John, Zheng Daniel, Etaix Nicolas</i>	

SOUND AND VIBRATION MEASUREMENTS AND ANALYSIS

THE STUDY ON THE FACTORS INFLUENCING THE PRECISION OF THE BLOCKING FORCE BASED TRANSFER PATH ANALYSIS	288
<i>Wu Xianjun</i>	
DYNAMIC RESPONSE OF STEEL-TIMBER COMPOSITE (STC) BEAMS	296
<i>Chiniforush Alireza A., Akbarnezhad Ali, Valipour Hamid, Dackermann Ulrike</i>	
MONITORING OF A TRAFFIC SIGN STRUCTURAL SUPPORT VIBRATIONS	304
<i>Pinjan Aniket, Zahui Marcellin</i>	

IDENTIFICATION OF VIBRATION PROPERTIES OF WHEEL LOADER DRIVELINE PARTS AS A BASE FOR ADEQUATE CONDITION MONITORING: BEARINGS	312
<i>Källström Elisabeth, Lindström John, Håkansson Lars, Karlberg Magnus, Öberg Olof</i>	
NOISE, VIBRATION AND COMBUSTION INTER-RELATIONSHIPS FOR A COMPRESSION IGNITION ENGINE FUELLED BY ETHANOL-DIESEL BLENDS	320
<i>Satsangi Dev Prakash, Tiwari Nachiketa, Agarwal Avinash Kumar</i>	
ASSESSMENT OF THE BONE-ACETABULAR IMPLANT CONTACT PROPERTIES DURING IMPACTS: A FINITE ELEMENT STUDY	328
<i>Nguyen Vu-Hieu, Haiait Guillaume</i>	
INVESTIGATION INTO POTENTIALLY DAMAGING EFFECTS TO BUILDING STRUCTURES AT LOCATIONS SURROUNDING MILITARY LAND RANGES IN THE UK DUE TO AIR OVERPRESSURE OR SEISMIC SHOCK	334
<i>Arthurs Ian, Methold Rick, Waters Adrian</i>	
AN INITIAL INVESTIGATION OF THE CORRELATION BETWEEN A NUMBER OF DRILLING RELATED QUANTITIES MEASURED DURING DOWN THE HOLE DRILLING	342
<i>Premachandran Rammohan Kodakadath, Linderholt Andreas, Håkansson Lars, Gothberg Mattias</i>	
SEMI-NATURAL TEST BENCH FOR BUOYANCY VARIATION SYSTEM OF UNDERWATER ROBOTS INVESTIGATIONS	350
<i>Gafurov Salimzhan, Salmina Vera, Greshnyakov Pavel, Mukhametzyanov Andrey, Handroos Heikki</i>	
DEVELOPMENT OF THE ELECTROMECHANIC BUOYANCY VARIATION SYSTEM OF UNDERWATER GLIDER	358
<i>Gafurov Salimzhan, Salmina Vera, Mukhametzyanov Andrey, Handroos Heikki</i>	
RESPONSE PREDICTION OF A MECHANICAL SYSTEM WITH VIRTUAL BOUNDARY CONDITIONS BASED ON THE BLOCKED TRANSFER FUNCTION METHOD	364
<i>Tan Songbin, Xu Hao, Sui Fusheng</i>	
 <u>ACTIVE STRUCTURAL ACOUSTIC CONTROL</u>	
EXPERIMENTAL TESTS OF A FLYWHEEL INERTIAL ACTUATOR	372
<i>Kras Aleksander, Gardonio Paolo</i>	
INTERNAL MODEL CONTROL OF A WASHING MACHINE CASING FOR ACTIVE NOISE REDUCTION	380
<i>Wrona Stanislaw, Mazur Krzysztof, Pawelczyk Marek</i>	
ADAPTIVE CONTROL OF RADIATED SOUND POWER BASED ON TIME-DOMAIN ESTIMATES OF ACOUSTIC RADIATION MODES	388
<i>Nor Khairul Affendy Md, Mace Brian, Hioka Yusuke</i>	
A STUDY ON THE RELATION BETWEEN THE ACTUATOR PLACEMENT AND THE CHARACTERISTICS OF THE SOUND RADIATED BY A PLATE STRUCTURE	396
<i>Papantoni Veatriki, Rose Michael, Monner Hans Peter</i>	
ADAPTIVE ACOUSTIC METASURFACES FOR THE NOISE SHIELDING	404
<i>Mokry Pavel, Vaclavik Jan, Necasek Jakub, Psota Pavel, Steiger Katerina, Vapenka David</i>	
EXPERIMENTAL IMPLEMENTATION OF SWITCHING AND SWEEPING PIEZOELECTRIC PATCH VIBRATION ABSORBERS	412
<i>Dal Bo Loris, Casagrande Daniel, Gardonio Paolo</i>	
ACTIVE VIBRATION CONTROL USING PID-AFC CONTROLLER OF THE PIEZO STACK ACTUATOR WITH CONSIDERATION TO HYSTERESIS AND SATURATION EFFECTS	420
<i>Mazlan Ahmad Zhafran Ahmad, Ripin Zaidi Mohd, Ali Wan Mohd Amri Wan Mamat</i>	
ACTIVE STRUCTURAL-ACOUSTIC CONTROL OF SOUND TRANSMISSION THROUGH A DOUBLE WALL PANEL BASED ON FREQUENCY WEIGHTED H2 – OPTIMAL CONTROLLER	428
<i>Bhattacharya Partha, Adhikari Biplab Ranjan, Sahu Atanu</i>	
 <u>ALGORITHMS FOR ACTIVE CONTROL</u>	
NON-FRAGILE OBSERVER-BASED CONTROLLER WITH AN APPLICATION TO ACTIVE VIBRATION ATTENUATION	435
<i>Oveisi Atta, Nestorovic Tamara</i>	
APPLICATION OF A ALL-PASS FILTER CASCADE TO ACTIVE VIBRATION CONTROL OF CANTILEVER BEAMS	443
<i>Tuma Jiri, Šuránek Pavel, Los Jaroslav, Mahdal Miroslav</i>	
LOCAL ACTIVE SOUND CONTROL USING THE REMOTE MICROPHONE TECHNIQUE AND HEAD-TRACKING FOR TONAL AND BROADBAND NOISE SOURCES	451
<i>Jung Woomin, Elliott Stephen, Cheer Jordan</i>	
DECENTRALISED ACTIVE VIBRATION CONTROL USING A REMOTE SENSING STRATEGY	459
<i>Cheer Jordan, Milton Joseph, Daley Steve</i>	
A METHOD FOR RE-ESTIMATING FEEDBACK PATH UNDER ACTIVE NOISE CONRTOL	467
<i>Fujii Kensaku, Muneyasu Mitsuji</i>	

ACTIVE, AND SEMI-ACTIVE CONTROL OF SOUND AND VIBRATION

EXPERIMENTAL MAXIMISATION OF THE POWER ABSORBED BY AN INERTIAL ACTUATOR FOR STRUCTURAL VIBRATION CONTROL	475
<i>Camperi Stefano, Ghandchi-Tehrani Maryam, Elliott Stephen J.</i>	
VIBRATION OBSERVATION AND CONTROL FOR THE TIP OF A MOTOR-DRIVEN TRANSLATIONAL FLEXIBLE MANIPULATOR BASED ON OPTIMAL CONTROL ALGORITHM	483
<i>Li Wei, Ju Jinyong</i>	
ENERGY STORING ACTUATORS FOR GROUND VEHICLES AND VIBRATION CONTROL	491
<i>Margolis Donald</i>	
NEW METHOD FOR ASSISTING ROTOR TO PASS THROUGH CRITICAL SPEEDS AND DYNAMIC BALANCING	499
<i>Xu Xueshan, Zhang Xiao-Zhang</i>	
OPTIMAL PLACEMENT OF SIX INERTIAL MASS ACTUATORS FOR MIMO ACTIVE VIBRATION CONTROL ON A LABORATORY TRUSS STRUCTURE	506
<i>Lapicciarella Giovanni, Rohlfing Jens, Tehrani Maryam Ghandchi</i>	
CONTROL OF AMPLITUDE, FREQUENCY AND PHASE OF AN HARMONIC ANTI-NOISE PNEUMATIC SOURCE	514
<i>Micheau Philippe, Burel Benjamin, Robert Raymond, Masson Patrice</i>	
A DEVELOPMENT OF NEW TYPE SPEAKER FEATURING VARIABLE RESONANT FREQUENCIES BY UTILIZING A MAGNETO-RHEOLOGICAL FOAM	522
<i>Lee Tae-Hoon, Yoon Ji-Youmh, Shin Sang Un, Choi Seung-Bok</i>	
CONTROLLING THE EFFECTIVE MATERIAL PROPERTIES USING AN ACTIVE NOISE CONTROL SYSTEM	526
<i>Cheer Jordan, Daley Steve</i>	
USE OF MAGNETIC BEARINGS IN VIBRATION CONTROL OF A STEAM TURBINE WITH OIL-FILM BEARINGS	534
<i>Pilotto Rafael, Nordmann Rainer, Atzdordt Heiko, Herold Sven</i>	
ACTIVE CONTROL OF LATERAL VIBRATION OF A SHAFT-HULL COUPLED SYSTEM	542
<i>Qin Hui, Zheng Hongbo, Qin Wenyuan, Zhang Zhiyi</i>	
A PI SHAPE PIEZOELECTRIC ACTUATOR FOR ACTIVE VIBRATION CONTROL APPLICATION	550
<i>Wang Wei, Yang Zhichun, Li Bin</i>	
STUDY ON LOCAL ACTIVE NOISE CONTROL WITHIN A SMALL SEMI-ENCLOSED SPACE	557
<i>Lei Chengyou, Zhang Jinlan, Li Pei, Sun Guocang, Li Xiaodong</i>	
EXPERIMENTAL INVESTIGATIONS OF A NONLINEAR MULTIMODAL VIBRATION ENERGY HARVESTER BASED ON MAGNETIC LEVITATION	564
<i>Ajmi Yahia, Kacem Najib, Bouhaddi Nouredine</i>	
ANALYSIS AND IMPLEMENTATION OF A MULTIPLE-SOURCE MULTIPLE-CHANNEL ACTIVE VIBRATION CONTROL OF LARGE STRUCTURES BASED ON FINITE ELEMENT MODEL IN-LOOP SIMULATION SYSTEM	571
<i>Liu Jinxin, Zhang Xingwu, Yang Liangdong, Chen Xuefeng, Gao Bei</i>	
ENERGY TRANSFER IN NONLINEAR VIBRATION ABSORBERS	579
<i>Zhang Yu, Liu Kefu, Xiong Liuyang, Tang Lihua</i>	
ELECTROMECHANICAL HYDRAULIC MOUNT	587
<i>Vahdati Nader</i>	
WAVE ABSORPTION OF A FLEXIBLE BEAM FOR BAND-LIMITED SPECTRA USING DIRECT FEEDBACK	593
<i>Iwamoto Hiroyuki, Kobayashi Hayata, Tanaka Nobuo</i>	
STUDY OF ELECTORHEOLOGICAL DAMPER FOR CONTROL OF ROTOR VIBRATION	599
<i>Naik Sachin, Patil Sharadchandra</i>	
NONLINEAR VIBRATION CHARACTERISTICS ANALYSIS OF THE AXIALLY MOVING PRINTING MEMBRANE	606
<i>Wu Jimei, Tian Zhen, Wang Yan, Shao Ming-Yue, Guo Xu-Xia</i>	

SOUND FIELD CONTROL AND 3D AUDIO

SOUND ZONES: ON ENVELOPE SHAPING OF FIR FILTERS	613
<i>Møller Martin Bo, Olsen Martin</i>	
DIFFERENCES IN THE NON LINEAR PROPAGATION OF CRACKLE AND SCREECH	621
<i>Punekar Jyothi, Avital Eldad, Motallebi Fariboz, Li Xiaodong</i>	
MULTI-ZONE REPRODUCTION OF A SHARED SOUND FIELD INCLUDING DISTANCE EFFECTS	628
<i>Shimizu Taku, Trevino Jorge, Sakamoto Shuichi, Suzuki Yōiti, Ise Tomohiko</i>	
METHODS FOR GENERATING MULTIZONE FIELDS WITH LOW RISK OF INTERFERENCE	636
<i>Poletti Mark</i>	
THE EFFECT OF ENCLOSURE COUPLING ON A DUAL-LAYER LINEAR LOUDSPEAKER ARRAY	644
<i>Cheer Jordan</i>	
A LOUDSPEAKER ARRAY FOR 2 PEOPLE TRANSAURAL REPRODUCTION	652
<i>Simon Marcos Felipe, Fazi Filippo Maria</i>	

SPATIAL DELTA-SIGMA MODULATION FOR DIRECTIVITY CONTROL OF AN ACOUSTIC PIXEL ARRAY USING CNT.....	660
<i>Kim Dong-Hwan, Choi Jung-Woo</i>	
INVESTIGATION OF THE GROUP LASSO ALGORITHM FOR SOUND FIELD REPRODUCTION: COMPARISON WITH THE LASSO AND ELASTIC-NET ALGORITHMS.....	668
<i>Gauthier Philippe-Aubert, Grandjean Pierre, Berry Alain</i>	
SYNTHESIS OF A SOUND FIELD INCLUDING VIRTUAL SCATTERING OBJECTS IN WAVE FIELD SYNTHESIS.....	676
<i>Hahn Nara, Spors Sascha</i>	
PARAMETRIC STUDY IN THE FORMATION OF A VIRTUAL SPEAKER AND BAFFLE ON A THIN PANEL.....	684
<i>Woo Jung-Han, Ih Jeong-Guon</i>	
AN OPTIMIZATION APPROACH TO CONTROL SOUND SOURCE SPREAD WITH MULTICHANNEL AMPLITUDE PANNING.....	689
<i>Franck Andreas, Fazi Filippo, Hamdan Eric</i>	
A SPATIAL AUDIO CODEC SYSTEM FOR ANALYSIS AND SYNTHESIS OF SOUND FIELDS	697
<i>Chiang Yi-Hao, Li Yi, Lo Yi-Yang, Bai Mingsian</i>	
EFFECT OF MULTIPOLE DICTIONARY IN SPARSE SOUND FIELD DECOMPOSITION FOR SUPER- RESOLUTION IN RECORDING AND REPRODUCTION.....	705
<i>Koyama Shoichi, Murata Naoki, Saruwatari Hiroshi</i>	
MICROPHONE SETS, PANNING FUNCTIONS AND CHANNEL OBJECTS.....	713
<i>Menzies Dylan, Fazi Filippo Maria</i>	
BINAURAL RENDERING OF SPHERICAL MICROPHONE ARRAY RECORDINGS BY DIRECTLY SYNTHESIZING THE SPATIAL PATTERN OF THE HEAD-RELATED TRANSFER FUNCTION	721
<i>Sakamoto Shuichi, Salvador Cesar, Trevino Jorge, Suzuki Yo-iti</i>	
COMPARISON OF MICROPHONE ARRAY GEOMETRIES FOR MULTI-POINT SOUND FIELD REPRODUCTION.....	729
<i>Coleman Philip, Galindo Miguel Blanco, Jackson Philip J.B.</i>	
DESIGN OF A SECONDARY SOURCE THAT MINIMIZES THE EFFECT ON THE REPRODUCTION AREA WHILE FORMING A QUIET AREA WHEN THE PRIMARY SOURCE IS PRESENT.....	737
<i>Ryu Homin, Wang Semyung, Kim Kihyun</i>	

ACTIVE NOISE AND VIBRATION CONTROL IN PRACTICAL SYSTEM IMPLEMENTATION

INFLUENCES OF COUPLE CONTROL POINTS ON MULTIPOINT-RESPONSE-CONTROLLED RANDOM VIBRATION TESTING.....	742
<i>Zhu Changchun, Yang Chong</i>	
PIEZOELECTRIC-BASED VERTICAL TAIL BUFFET VIBRATION SUPPRESSION USING MODIFIED POSITIVE POSITION FEEDBACK.....	749
<i>Niu Wenchao, Li Bin, Zou Chengzhe, Zhang Shengkun</i>	

VOLUME 2

NUMERICAL MODEL OF VIBRATION CONTROL STRATEGY FOR TRUCK-MOUNTED CONCRETE PUMP BOOMS.....	756
<i>Liu Huiyong, Xiong Yeping, Zhao Qing</i>	
ACTIVE CONTROL OF SURFACE ROBOT POSITION	764
<i>Gafurov Salimzhan, Mukhametzyanov Andrey, Salmina Vera, Handroos Heikki</i>	
ANALYSIS, DESIGN AND OPTIMIZATION OF A NONLINEAR ENERGY HARVESTER.....	773
<i>Diala Uchenna, Lang Zi-Qiang, Pope Simon</i>	
FULLY DIGITAL IMPLEMENTATION OF A HYBRID FEEDBACK STRUCTURE FOR BROADBAND ACTIVE NOISE CONTROL IN HEADPHONES.....	781
<i>Benois Piero Rivera, Nowak Patrick, Zoelzer Udo</i>	
A LINE-SPECTRUM ACTIVE NOISE CONTROL SYSTEM WITH MULTI-FREQUENCY ESTIMATION BASED ON PARALLEL ADAPTIVE NOTCH FILTER.....	789
<i>Wang Han, Sun Hongling, Sun Yunping, Wu Ming</i>	

APPLICATIONS OF ACTIVE CONTROL

CONTROLLING INCIDENT SOUND FIELDS WITH SOURCE ARRAYS IN FREE SPACE AND THROUGH APERTURES.....	797
<i>Elliott Stephen, Cheer Jordan, Lam Bhan, Shi Chuang, Gan Woon-Seng</i>	
A MIXED FREQUENCY DOMAIN ADAPTIVE ALGORITHM OPTIMIZED FOR ACTIVE CONTROL IN NON-CAUSAL SCENARIOS.....	804
<i>Lu Jing, Kai Chen</i>	
SPEECH QUALITY ENHANCEMENT IN DIGITAL HEARING AIDS: AN ACTIVE NOISE CONTROL APPROACH.....	811
<i>Pradhan Somanath, Bhattacharjee Sankha, Patel Vinal, George Nithin</i>	

EFFECTS OF PHYSICAL CONFIGURATIONS ON ANC HEADPHONE PERFORMANCE	819
<i>Wu Lifu, Qiu Xiaojun, Ma Jin, Guo Yecai</i>	
ACTIVE NOISE CONTROL SYSTEMS FOR OPEN WINDOWS: CURRENT UPDATES AND FUTURE PERSPECTIVES.....	827
<i>Lam Bhan, Shi Chuang, Gan Woon-Seng</i>	
RECENT ADVANCES ON ACTIVE CONTROL OF SOUND TRANSMISSION THROUGH VENTILATION WINDOWS.....	834
<i>Qiu Xiaojun</i>	
EXPERIMENTAL IMPLEMENTATION OF MULTIPLE-INPUT MULTIPLE-OUTPUT ACTIVE VIBRATION CONTROL ON VIBRATION ISOLATION SYSTEMS.....	842
<i>Zhang Peng, He Fangpo</i>	
DYNAMIC ISOTROPIC DESIGN AND DECENTRALIZED ACTIVE CONTROL OF A SIX-DOF MICRO-VIBRATION ISOLATOR LYING ON TWO RINGS FOR SPACE SYSTEMS	850
<i>Yang XiaoLong, Wu HongTao, Li Yao, Kang ShengZheng, Chen Bai</i>	
FXLMS-BASED ADAPTIVE VIBRATION CONTROL OF VERTICAL TAIL.....	858
<i>Li Bin, Zou Chenzhe, Niu Wenchao, Wang Wei</i>	
ACTIVE VIBRATION CONTROL OF FERROMAGNETIC BEAMS AND PLATES USING JOULE AND VILLARI EFFECT	864
<i>Glugla Markus, Schulz Ralf Kiran, Müller Petra</i>	

AIRCRAFT CABIN NOISE AND VIBRATION CONTROL

SOUND TRANSMISSION ACROSS FINITE CLAMPED DOUBLE-WALL SANDWICH PANELS IN THE PRESENCE OF EXTERNAL MEAN FLOW	872
<i>Catalan Jean-Cedric, Liu Yu</i>	
ANALYSIS OF THE VIBRO-ACOUSTIC COUPLING FIELD IN RECTANGULAR CAVITY WITH A CLAMPED FLEXIBLE PANEL.....	880
<i>Su Changwei, Zhu Haichao, Mao Rongfu, Li Jiujiang</i>	
NONLINEAR VIBRATION ANALYSIS OF COMPOSITE LAMINATED PLATES USING THE FEM	887
<i>Jiang Guoqing, Li Fengming</i>	
EXPERIMENTAL INVESTIGATION OF ACOUSTIC AND VIBROACOUSTIC CHARACTERISTICS OF COMPOSITE PANELS.....	893
<i>Zverev Aleksander, Chernyh Valery, Mikhaylov Sergey</i>	
REDUCTION OF AIRCRAFT ENGINE NOISE BY COVERING SURFACE ACOUSTIC METAMATERIALS ON SIDEWALLS	901
<i>Wang Xiaole, Huang Zhenyu, Han Feng, Feng Zixin</i>	
NUMERICAL PREDICTION OF CABIN NOISE DUE TO JET NOISE EXCITATION OF TWO DIFFERENT ENGINE CONFIGURATIONS.....	909
<i>Blech Christopher, Appel Christina K., Delfs Jan W., Langer Sabine C.</i>	
VIBRO-ACOUSTIC DESIGN OF AN ACTIVE WINDOW FOR AIRCRAFT INTERIOR NOISE REDUCTION.....	917
<i>Dimino Ignazio</i>	

AVIATION NOISE

CALCULATION OF AIRCRAFT NOISE EXPOSURE IN GERMANY	925
<i>Myck Thomas, Vogelsang Berthold</i>	
SURVEY OF NOISE ATTITUDES 2014	931
<i>Rhodes Darren, Notley Hilary, Turner Stephen</i>	
DRONE ON: A PRELIMINARY INVESTIGATION OF THE ACOUSTIC IMPACT OF UNMANNED AIRCRAFT SYSTEMS (UAS)	939
<i>Kloet Nicola, Watkins Simon, Wang Xu, Clothier Reece, Palmer Jennifer, Prudden Sam</i>	
NOISE ASSESSMENT OF AIRCRAFT WITH DISTRIBUTED ELECTRIC PROPULSION USING A NEW NOISE ESTIMATION FRAMEWORK.....	947
<i>Synodinos Athanasios, Self Rod, Torija Antonio</i>	
VALIDATION OF NOISE FOOTPRINT CALCULATION MODEL FOR A HIGH PERFORMANCE MILITARY AIRCRAFT	955
<i>Grigat Ernst</i>	

ACOUSTIC SIMULATION, TEST AND CONTROL IN SPACECRAFT

CLASSIFICATION OF THE MID-FREQUENCY RANGE BASED ON SPATIAL FOURIER DECOMPOSITION OF OPERATIONAL DEFLECTION SHAPES	963
<i>Biedermann Jörn, Winter René, Wandel Martin, Norambuena Marco, Böswald Marc</i>	
THE INVESTIGATION FOR ACOUSTIC FATIGUE ON COMPOSITE SOLAR PANEL	971
<i>Li Ye, Yang Jiang, Xiang Shuhong, Zheng Ling, Zhang Wei</i>	
THE THERMAL PROTECTION AND TEST VERIFICATION FOR HYPERSONIC FLIGHT VEHICLES BY FILM COOLING	979
<i>Xiang Shuhong, Zhang Mingjie, Yang Yanjing, Wang Yuchen, Li Ye, Zhang Jungang, Yan Tingfei, Wang Jing</i>	

SOUND SYNTHESIS USING SOURCE ARRANGEMENTS WITH ACTIVE AND REACTIVE SOUND MODES	987
<i>Merlo Clinton Andre, Paqual Alexander M., Medeiros Eduardo Bauzer</i>	
THE COUPLED STRUCTURAL-ACOUSTIC ANALYSIS OF SPACECRAFT SOLAR ARRAYS BASED ON THE FEM-BEM METHOD	993
<i>Zou Yuanjie, Gao Qiang, Zhu Weihong, Han Zengyao</i>	
INFLUENCE OF FILL EFFECT ON PAYLOAD IN A LARGE LAUNCH VEHICLE FAIRING	1001
<i>Zheng Ling, Xiang Shuhong</i>	
INVESTIGATION OF THE VIBROACOUSTICAL CHARACTERISTICS OF THE GAS-TURBINE ENGINE NK-14ST FUEL-CONTROL SYSTEM	1009
<i>Mironova Tatiana</i>	
STRUCTURAL ACOUSTIC RADIATION OPTIMIZATION OF A TRUNCATED CONICAL SHELL BASED ON FINITE ELEMENT METHOD	1015
<i>Chen Hongyong, Fan Xuanhua, Li Shangming, Wang Dong</i>	
EXAMINATION OF THE STRUCTURAL RESPONSE OF THE ORION EUROPEAN SERVICE MODULE TO REVERBERANT AND DIRECT FIELD ACOUSTIC TESTING	1023
<i>McNelis Mark E, Le-Plenier Cyprien, Hughes William O, Fogt Vincent A, Ngan Ivan C S, Thirkettle Anthony C, Skinner Mitch, Larko Jeffrey M, Bittinger Samantha A, Larkin Paul</i>	
APPLICATION OF COMPLEX TDOFS IN FIXED BOUNDARY PAYLOADS VIBRATION TESTS	1031
<i>Ding Yiting, Wang Ke, Yang Zhengxi</i>	

AEROACOUSTICS

DESIGN OF ACTIVE FLUIDIC INJECTION SYSTEMS FOR JET-NOISE REDUCTION THROUGH STOCHASTIC RECONSTRUCTION OF TURBULENT FLOW FIELDS	1039
<i>Barbarino Mattia, Ilsami Mario, Tuccillo Raffaele, Federico Luigi</i>	
EXPERIMENTAL INVESTIGATION OF ACOUSTIC EFFICIENCY OF CHEVRON NOZZLES FOR HIGH BY-PASS AVIATION ENGINE	1047
<i>Mironov Alexey, Krashennnikov Sergey, Maslov Vladimir</i>	
AN INVESTIGATION ON THE SOURCES OF JET NOISE	1053
<i>Musafir Ricardo</i>	
AIRFOIL LEADING EDGE NOISE PREDICTIONS USING A VISCOUS MEAN FLOW	1057
<i>Sun Yuhao, Fattah Ryu, Zhang Xin</i>	
ASYMPTOTIC THEORY OF CONTRA-ROTATING ADVANCED OPEN ROTOR WAKE INTERACTION NOISE	1065
<i>Kingan Michael</i>	
PREDICTION FOR NOISE REDUCTION AND CHARACTERISTICS OF FLOW INDUCED NOISE ON AXIAL COOLING FAN	1073
<i>Minorikawa Gaku, Lim Tae-Gyun, Jeon Wan-ho</i>	
EVALUATION OF DIFFERENT METHODS IN COMPUTATIONAL AEROACOUSTICS FOR NOISE PREDICTION AND MINIMIZATION OF A ROD-AIRFOIL CONFIGURATION	1081
<i>Zhou Beckett Yuxiang, Silva Carlos Roberto Ilario da, Albring Tim, Economon Tom, Gauger Nicolas R., Alonso Juan J</i>	
AN IMPROVED INVERSE-PHASED ARRAY METHOD FOR ESTIMATING FREE-FIELD ENGINE CORE NOISE SPECTRA FROM MEASUREMENTS IN REVERBERANT TEST CELLS	1089
<i>Tester Brian</i>	
FAN NOISE REDUCTION INCLUDING THE EFFECTS OF SWEEPED-AND-LEANED VANES AND ACOUSTIC TREATMENT	1097
<i>Zhang Weiguang, Wang Xiaoyu, Sun Xiaofeng</i>	
UNMANNED AIRCRAFT DESIGN WITH MINIMUM ACOUSTIC FOOTPRINT	1104
<i>Benassi Luca</i>	
DEVELOPMENT OF EXPERIMENTAL METHOD FOR AZIMUTHAL MODE MEASUREMENT FOR JET-WING INTERACTION NOISE	1110
<i>Kopiev Victor, Faranosov Georgy, Belyaev Ivan, Bychkov Oleg, Zaytsev Mikhail</i>	
A NEW METHOD OF CONTROLLING FLUTTER OF CASCADE BLADES BASED ON A GENUINE THREE-DIMENSIONAL MODEL	1118
<i>Wang Xiaoyu, Qu Ruwen, Sun Xiaofeng</i>	

EXPERIMENTAL AEROACOUSTICS

ACOUSTIC CORRECTIONS FOR A KEVLAR WALL WIND TUNNEL USING A PULSED-LASER POINT SOURCE	1126
<i>Pascioni Kyle, Colangelo Andrew, Cattafesta Louis</i>	
A LIGHT-WEIGHT ACOUSTIC SILENCER DESIGN FOR A MULTI-ROTOR MAV	1134
<i>Debiasi Marco, Lu Zhenbo, Khoo Boo Cheong, Boon Seet Ju</i>	
NOISE MEASUREMENTS OF FLAPPING WINGS WITH TENSED MEMBRANE	1142
<i>Debiasi Marco, Lu Zhenbo, Nguyen Quoc Viet, Chan Woei Leong</i>	
INFLUENCE OF THE CASING TREATMENT DESIGN PARAMETERS ON THE DUCTED COUNTER ROTATING FAN NOISE	1150
<i>Khaletskii Iurii, Pochkin Yaroslav, Korznev Vladimir, Mileschin Victor</i>	

A NON-INVASIVE METHODOLOGY FOR MODAL CHARACTERISATION OF AN AIRCRAFT CABIN USING HIGH SPEED 3D DIGITAL IMAGE CORRELATION	1158
<i>Molina-Viedma Ángel Jesús, López-Alba Elías, Felipe-Sesé Luis, Díaz Francisco, Rodríguez-Ahlquist Javier, Iglesias-Vallejo Manuel</i>	
ON THE USE OF ACTIVE FLOW CONTROL FOR AEROFOIL NOISE REDUCTION	1166
<i>Szoke Mate, Azarpeyvand Mahdi</i>	
AERO-ACOUSTICS CHARACTERISTICS OF LAMINAR JETS OVER A FLAT PLATE.....	1174
<i>Rahul S Arackal, Jothi T J S</i>	
FLOW INDUCED NOISE STUDIES ON A POROUS TRAILING SURFACE OF A FLAT PLATE	1179
<i>Sumesh C.K, T.J.S Jothi</i>	
BOUNDARY LAYER FLOW INTERACTION WITH POROUS SURFACES	1186
<i>Ali Syamir Alihan Showkat, Azarpeyvand Mahdi, da Silva CarlosR. Ilario da</i>	
ACTIVE CHEVRONS FOR JET NOISE REDUCTION.....	1194
<i>Mohan Nagendra Karthik Depuru, Doty Michael</i>	
A 3 MICROPHONE METHOD TO SEPARATE DIRECT AND INDIRECT COMBUSTION NOISE INSIDE A TURBOFAN JET ENGINE ANNULAR COMBUSTOR.....	1202
<i>Hart Anthony, Holland Keith, Joseph Phillip</i>	
 <u>LOW MACH NUMBER AEROACOUSTICS</u>	
VIBRATION AND SOUND OF A HIGHLY-ELASTIC THIN AIRFOIL	1210
<i>Manela Avshalom, Weidenfeld Michael</i>	
AERODYNAMIC AND AEROACOUSTIC RE-DESIGN OF LOW-SPEED BLADE PROFILE	1218
<i>Yan Yan, Avital Eldad, Shen Xiang, Junhui Gao, Li Xiaodong, Korakianitis Theo, Zhao Qinghe</i>	
AERODYNAMIC NOISE OF BLADE GRILL HVAC SYSTEMS AT LOW MACH NUMBER.....	1226
<i>Kralicek Jan, Kucera Miroslav</i>	
EXPERIMENTAL OBSERVATIONS OF FLOW-ACOUSTIC FEEDBACK PHENOMENA IN DUCTS	1234
<i>Ville Jean-Michel, Papaxanthos Nicolas, Perrey-Debain Emmanuel, Moreau Solène, Bennouna Saad</i>	
 <u>COMPUTATIONAL AEROACOUSTICS</u>	
DEVELOPMENT AND APPLICATION OF OPTIMISED COMPACT DIFFERENCE SCHEMES TO LINEAR ACOUSTICS PROBLEMS IN ORTHOGONAL CURVILINEAR COORDINATES	1242
<i>Beckwith Christopher, Bojarevics Valdis, Pericleous Koulis</i>	
ASYMMETRIC FINITE DIFFERENCES FOR NON-CONSTANT-AMPLITUDE WAVES	1250
<i>Brambley Ed</i>	
A COMPRESSIBLE IMMERSED BOUNDARY METHOD FOR THE FLOW-INDUCED NOISE SIMULATION	1258
<i>Cheng Long, Du Lin, Jing Xiaodong, Sun Xiaofeng, Hu Guotun</i>	
MODEL ORDER REDUCTION IN COMPUTATIONAL AEROACOUSTICS	1266
<i>Arina Renzo</i>	
MODELLING THE UNSTEADY FLOW AND SHOCK-ASSOCIATED NOISE FROM DUAL-STREAM TURBULENT JETS.....	1272
<i>Rona Aldo, Mancini Alessandro, Hall Edward</i>	
EFFECT OF AIRPORT SURFACE AND JET BLAST DEFLECTOR ON SUPERSONIC JETS NOISE USING RANS/ILES-METHOD	1280
<i>Benderskiy Leonid, Lyubimov Dmitriy, Chestnyh Alexandra</i>	
NUMERICAL INVESTIGATION OF THE ACOUSTIC SCATTERING BEHAVIOR OF A BUTTERFLY VALVE	1288
<i>Denayer Hervé, Gracia María Muriel, Orselli Reinaldo Marcondes, De Roeck Wim, Desmet Wim</i>	
EXPERIMENTAL AND NUMERICAL INVESTIGATION OF RESONATOR BASED ACOUSTIC DAMPING	1296
<i>Grimm Felix, Stohr Michael, Dierke Jürgen, Ewert Roland, Noll Berthold, Aigner Manfred</i>	
EFFECTS OF OSCILLATING PLATES ON AEROACOUSTIC SOUND RADIATED FROM A CASCADE OF FLAT PLATES.....	1304
<i>Tanaka Yuya, Yokoyama Hiroshi, Iida Akiyoshi</i>	
THE EFFECT OF SLAT TRAILING EDGE THICKNESS ON THE NOISE FROM A 30P30N HIGHLIFT CONFIGURATION	1312
<i>Gao Junhui, Li Xiaodong, Lin Dakai</i>	
EFFICIENT METHOD FOR CAR EXTERIOR NOISE PREDICTION BASED ON STEADY CFD INPUT	1320
<i>Detandt Yves, Cabrol Marie, Talbot Alexis</i>	
ASSESSMENT OF ENGINE NOISE SHIELDING BY THE WINGS OF CURRENT TURBOFAN AIRCRAFT	1328
<i>Vieira Ana, Snellen Mirjam, G. Simons Dick</i>	
 <u>COMMUNITY AND ENVIRONMENTAL NOISE</u>	
REFLECTION OF AN URBAN FORM TO A SOUND ENVIRONMENT	1336
<i>Yu Lei, Xu Dong Chao, Sun Yun Hai, Liang Dui Dui, Kang Jian</i>	

STUDY ON ENVIRONMENTAL NOISE POLLUTION IN THREE AREAS OF THE CITY OF SANTIAGO DE CALI - COLOMBIA	1341
<i>Jimenez Luis Alberto Tafur, Villegas Jonathan Ochoa, Sanchez Santiago Ruiz, Acevedo Monica Duque</i>	
QUIET TECHNOLOGIES FOR DELIVERIES IN URBAN ENVIRONMENTS	1348
<i>Tansey Naomi, Waddington David, Davies William J</i>	
METROLOGY FOR INFRASOUND MEASUREMENTS	1356
<i>Kling Christoph, Fedtke Thomas, Soares Zemar Mearntins Defilippo, Milhomem Thiago</i>	
URBAN SOUNDSCAPE ANALYSIS: THE CASE STUDY OF THE DEPARTMENT OF HUMAN ARTS OF ROMA TRE UNIVERSITY	1360
<i>Asdrubali Francesco, Guattari Claudia, Evangelisti Luca, Marrone Paola, Orsini Federico, Grazieschi Gianluca</i>	
 <u>PASSIVE NOISE AND VIBRATION CONTROL</u>	
INCORPORATING SONIC CRYSTALS IN WINDOWS FOR NOISE ATTENUATION	1368
<i>Lim Kian-Meng, Lee Hsiao Mun, Tan Long Bin, Lee Heow Pueh</i>	
A NOVEL NOISE REDUCTION TECHNIQUE FOR AN AIR-COOLED CASE	1374
<i>Dincer Ayse, Etiz Ugur</i>	
 <u>NOISE MAPPING AND NOISE CONTROL IN URBAN AGGLOMERATIONS</u>	
NOISE IN EUROPE, SOME OBSERVATIONS BY CITIES	1382
<i>Wolfert Henk</i>	
ANALYSIS AND CHARACTERIZATION OF THE ROAD TRAFFIC IN THE NOISE MAPPING OF VENICE	1386
<i>Sepulcri Daniele, Remigi Francesca, Buoso Alessandro, Scarpa Angelo</i>	
 <u>SOUNDSCAPE</u>	
SENSESCAPES FASCILITATING LIFE QUALITY	1392
<i>Mossberg Frans</i>	
THE EFFECTS OF DIFFERENT CONFIGURATIONS OF NEIGHBORHOOD SCENERIES AND COMBINED NOISES ON SOUND PERCEPTIONS	1400
<i>Xu J M, Leung T M, Chau C K, Tang S K</i>	
A SOUNDWALK STUDY WITH EEG TEST IN THE MOUNTAINOUS URBAN PARK	1408
<i>Li Heng, Xie Hui, Xin Shang</i>	
COMPARATIVE STUDY ON SOUND PREFERENCES BETWEEN CHINESE AND ENGLISH RURAL TOURISTS	1414
<i>Ren Xinxin, Kang Jian</i>	
SOUNDSCAPE CHARACTERIZATION AND CLASSIFICATION: A CASE STUDY	1422
<i>Brambilla Giovanni, Pedrielli Francesca, Masullo Massimiliano</i>	
 <u>ENVIRONMENTAL NOISE AND HEALTH</u>	
PEOPLE, POLICY, AND HEALTH: ASSESSING HISTORIC INTERVENTIONS IN PRACTICE	1430
<i>Dryden Stuart</i>	
 <u>ENVIRONMENTAL NOISE MONITORING</u>	
NOISE MONITORING IN EU	1438
<i>Wolfert Henk</i>	
LIFE DYNAMAP: THE REAL TIME MAPPING SYSTEM COMES TO LIFE	1442
<i>Bellucci Patrizia, Peruzzi Laura, Zambon Giovanni</i>	
ANOMALOUS NOISE EVENTS CONSIDERATIONS FOR THE COMPUTATION OF ROAD TRAFFIC NOISE LEVELS: THE DYNAMAP MILAN CASE STUDY	1450
<i>Zambon Giovanni, Bisceglie Alessandro, Benocci Roberto, Orga Ferran, Socoro Carrie Joan Claudi, Alias Pujol Francesc, Alsina-Pages Rosa Maria</i>	
IMPLEMENTING THE HARMONICA INDEX IN THE DYNAMAP PROJECT	1458
<i>Peruzzi Laura, Bellucci Patrizia, Bisceglie Alessandro, Brambilla Giovanni, Zambon Giovanni</i>	
EXPLORING THE BIG ACOUSTIC DATA GENERATED BY AN ACOUSTIC SENSOR NETWORK DEPLOYED AT A CROSSRAIL CONSTRUCTION SITE	1466
<i>Piper Ben, Barham Richard, Sheridan Steve, Sotirakopoulos Kostas</i>	
INDUSTRIAL NOISE IMPACT ASSESSMENT USING PRACTICAL APPLICATION OF BS4142:2014 TO A COMPLEX REAL LIFE CASE	1474
<i>Tofts Jon, Clayton Tony, Waddington David</i>	
MEASUREMENT UNCERTAINTY IN ENVIRONMENTAL NOISE SURVEYS: COMPARISON OF FIELD TEST DATA	1480
<i>Fenlon John, Whitfield Bill</i>	

DESIGN OF A PROTOTYPE OF A SMART NOISE MONITORING SYSTEM	1488
<i>Borchi Francesco, Bartalucci Chiara, Carfagni Monica, Governi Lapo, Furferi Rocco, Silvaggio Rosalba, Curcuruto Salvatore, Nencini Luca</i>	

WIND TURBINE NOISE

AN ENVIRONMENTAL HEALTH OFFICER'S EXPERIENCE IN ASSESSING WIND ENERGY NOISE IMPACT ASSESSMENTS - BEFORE AND AFTER THE PUBLICATION OF THE INSITUTE OF ACOUSTICS GOOD PRACTICE GUIDE.....	1496
<i>Jordan Chris</i>	
DO WIND FARM NOISE CONTROLS IN THE UK WORK?	1504
<i>Lewis Toby</i>	

VOLUME 3

A METHOD TO CONTROL AMPLITUDE MODULATION IN WIND TURBINE NOISE UNDER UK PLANNING REGIME	1512
<i>Perkins Richard, Lotinga Michael</i>	
STUDY OF THE IMPACT OF NOISE POLLUTION IN THE WIND FARM: CASE OF AL KOUDIA AL BAIDA WIND FARM - TETOUAN	1520
<i>Ammar Adil, Garoum Mohammed, Bousshine Said, Boubel Ayoub, Bybi Abdelmajid</i>	
INFLUENCE OF BACKGROUND NOISE AND FREQUENCY ANALYSIS OF WIND TURBINE NOISE	1528
<i>Desarnaulds Victor, Magnin Dimitri, Fecelier Ronan</i>	
TONAL NOISE MITIGATION ON WIND TURBINES	1536
<i>Stauber Jutta, Marmo Brett, Black Donald</i>	
WIND TURBINE NOISE HIGH FREQUENCY TONALITY - SOURCES AND EVALUATION AT NEAR FIELD EMISSION COMPARED TO FAR FIELD IMMISSION LOCATIONS.....	1544
<i>Fiumicelli Dani, Seddon James</i>	

METASTRUCTURES FOR NOISE AND VIBRATION CONTROL

METRASTRUCTURES FOR NOISE AND VIBRATION CONTROL.....	1552
<i>Attenborough Keith, Shin Ho-Chul, Taherzadeh Shahram, Schwan Logan, Umnova Olga, El Ouahabi Abdelhalim Azbaid, Krylov Victor</i>	
SURFACE WAVES DUE TO PERIODICALLY-SPACED STRIPS ON AN ACOUSTICALLY-HARD SURFACE	1560
<i>Stronach Alexander, Taherzadeh Shahram, Attenborough Keith</i>	
EFFECTIVE BEHAVIOUR OF CORRUGATED RESONANCE SURFACE EMERGING FROM NEAR-FIELD INTERACTIONS	1568
<i>Schwan Logan, Umnova Olga, Boutin Claude</i>	
USE OF STOCHASTICALLY ROUGH SURFACES FOR CONTROL OF TRAFFIC-INDUCED GROUND VIBRATIONS	1576
<i>Krylov Victor</i>	
RAINBOW-TRAPPING ABSORBERS FOR TRANSMISSION PROBLEMS: BROADBAND AND PERFECT SOUND ABSORBING PANELS	1584
<i>Jimenez Noé, Vicent Romero-Garcia, Pagneux Vincent, Groby Jean-Philippe</i>	
ABSORBING AND MANIPULATING SOUND WITH METAMATERIALS.....	1589
<i>Hibbins Alastair, Rance Helen, Sambles Roy, Starkey Tim, Smith John, Ward Gareth</i>	
LOW FREQUENCY SOUND ABSORPTION THROUGH A MUFFLER WITH METAMATERIAL LINING	1594
<i>Sharma Neha, Umnova Olga, Moorhouse Andy</i>	

SOUND AND VIBRATION IN URBAN ENVIRONMENTS

GOOD PRACTICE CASE STUDY OF MANAGING CONSTRUCTION NOISE IN CENTRAL LONDON	1602
<i>Liu Yuyou, Gao Yan, Hu Wencheng, Shields Paul</i>	
A COMPARISON OF THE SUBJECTIVE AND REFERENCE METHODS FOR EVALUATING THE TONAL CHARACTER CORRECTION IN BS 4142:2014.....	1609
<i>Torjussen Matt</i>	
ESTIMATING THE CONTRIBUTION OF PUBLIC TRANSPORT BUSES TO THE TOTAL TRAFFIC NOISE IN SANTIAGO DE CHILE.....	1617
<i>Arenas Jorge, Suarez Enrique, Cardenas Jorge</i>	
SUITABILITY OF NATURAL SOUNDS TO ENHANCE SOUNDSCAPE QUALITY IN URBAN RESIDENTIAL AREAS.....	1625
<i>Hong Joo-Young, Lam Bhan, Gupta Rishabh, Gan Woon-Seng, Chong Shyh Hao, Feng Jing, Ong Zhen-Ting</i>	
AN EVIDENCE-BASED SOUNDSCAPE TAXONOMY	1631
<i>Bones Oliver, Cox Trevor, Davies William</i>	
INVESTIGATING THE ANNOYANCE OF CATTLE GRID NOISE	1638
<i>Pheasant Robert, Watts Greg, Khan Amir</i>	

ACOUSTIC ENVIRONMENT AND URBAN SUSTAINABLE DEVELOPMENT IN THE CITY OF CÁCERES	1646
<i>Rey-Gozalo Guillermo, Barrigón-Morillas Juan-Miguel, Montes-González David, Venegas-Jiménez Carmen, Bonilla-Medina Diego, Casas-Escudero Guadalupe, Méndez-Sierra Juan-Antonio, Vilchez-Gómez Rosendo, Atanasio-Moraga Pedro</i>	

OUTDOOR NOISE MODELLING, MAPPING AND SOLUTIONS FOR MITIGATION

MANAGING THE 2ND ROUND OF STRATEGIC NOISE MAPPING AND ACTION PLANNING ON NATIONAL MOTORWAY NETWORK.....	1654
<i>Štimac Alan</i>	
ACTIVITIES AND EXPERIENCES WITH QUALITY ASSURANCE OF CNOSSOS-EU IMPLEMENTED IN SOFTWARE	1662
<i>Probst Wolfgang</i>	
UNCERTAINTY IN NOISE MODELLING.....	1668
<i>Shilton Simon</i>	
EXPERIENCES WITH ISO 17534 AND FUTURE QUALITY REQUIREMENTS FOR CNOSSOS-EU	1676
<i>Banda Erwin Van Hartog, Verheij Theo</i>	
A COMPUTATIONAL ANALYSIS OF SOUND DIRECTIVITY FROM SOUND PROPAGATION THROUGH NON-ISOTHERMAL, TURBULENT EXHAUST JETS IN CROSS-FLOW	1682
<i>Leav Orddom, Cazzolato Benjamin, Howard Carl</i>	
PREDICTION OF THE AUDIBLE NOISE GENERATED BY CORONA DISCHARGE ON A POWER TRANSMISSION LINE: A MODEL VALIDATION	1690
<i>Piana Edoardo, Donini Alberto, Spezie Roberto, Turri Roberto, Cortina Rosario</i>	
NOISE MAPPING FOR LARGE REGIONS AND EXTRA BENEFITS	1697
<i>Stapelfeldt Hartmut, Zacharias Frank-Christian</i>	

PHYSICAL ACOUSTICS

MECHANICAL ADMITTANCE BASED PHYSICAL ATTRIBUTES REPRESENTATIONS OF RIBBED PLATES.....	1704
<i>Chen Kean, Tian Xuhua, Yan Shenggang</i>	
DISPERSION PROPERTIES OF MAGNETOACOUSTIC WAVES IN PLASMA WITH NON-ADIABATIC PROCESSES.....	1712
<i>Zavershinskii Dmitrii, Molevich Nonna, Riashchikov Dmitrii</i>	
PERFORMANCE INDICATORS OF LINEAR ALTERNATORS AT DIFFERENT ELECTRIC LOADS UNDER THERMOACOUSTIC-POWER-CONVERSION CONDITIONS	1719
<i>Abdelwahed Ahmed, Ibrahim Abdelmaged, Abdel-Rahman Ehab</i>	
MEASUREMENT OF DIELECTRIC PROPERTIES OF MEDIUM USING WAVE TRANSMISSIBILITY IN TERAHERTZ REGION.....	1727
<i>Kwak Yunsang, Park Sangmok, Park Junhong</i>	
THE APPLICATION OF RADIAL POINT INTERPOLATION MESHLESS METHOD BASED ON THE HERMITE COLLOCATION METHOD IN THE ACOUSTIC FIELD.....	1730
<i>Zhang Xinyu, Zhu Xiaosong, Zhao Xiaochen</i>	
SOMMERFELD EFFECT AND CRITICAL BEHAVIOR OF A NON-IDEAL ASYMMETRIC SYSTEM	1737
<i>Shin Eung-Soo, Kim Kee-Sung</i>	

ULTRASOUND, ULTRASONIC MEASUREMENTS AND THEIR APPLICATION

ULTRASONIC MECHANISM OF MICRO PATTERN REPLICATION ON GLASSY POLYMER FILMS	1745
<i>Xu Junsheng, Li Jin, Chen Enlei, Liu Changjun</i>	
ESTIMATION OF POROSITY AND MOISTURE CONTENT IN POLYMER COMPOSITES USING THERMO-ACOUSTIC WAVES.....	1753
<i>Bhat R M, Mahapatra D Roy</i>	
MEASUREMENTS OF ULTRASONIC CAVITATION IN LIQUIDS AND TISSUE MIMICKING MATERIALS	1761
<i>Troia Adriano, Nicola Pietro De</i>	
DEVELOPING A CLEANING SYSTEM FOR EDIBLE BIRD'S NEST USING TURBULENT FLOW AND ULTRASONIC WAVES.....	1769
<i>Thida Worakrit, Danworaphong Sorasak</i>	
GAS LEAK DETECTION STUDY IN A CUBE USING ULTRASONIC SPECTRAL SOUND FIELD VARIATION	1776
<i>Park Kang-Ho, Lee Sung Q</i>	
EXPEDITING GROWTH RATE OF BOTRYOCOCCUS BRAUNII USING 37- AND 80-KHZ ULTRASONIC WAVES.....	1782
<i>Salaeh Asleena, Boonphasuk Suwaphat, Danworaphong Sorasak</i>	

PASSIVE NOISE AND VIBRATION CONTROL

GUIDED AND CONVECTED ACOUSTIC WAVE COUPLED WITH YELDING WALLS : WHAT KIND OF COUPLING ?.....	1788
<i>Martin Vincent</i>	
THEORETICAL ANALYSIS OF VIBRATION TRANSMISSION CHARACTERISTICS OF AUDIO-BASE AND EXPERIMENTAL RESULT -- SHAPED IN EXPONENTIAL HORN --	1796
<i>Kita Masahide, Nishimura Kiminobu, Manpuku Kenji</i>	
A STUDY ON VIBRATION TRANSMISSION CHARACTERISTIC OF AN AUDIO-BASE BY USING FOUR-TERMINAL CONSTANTS OF ELECTRIC NETWORK	1804
<i>Nishimura Kiminobu, Kita Masahide</i>	

CAVITATION AND MATERIALS SCIENCE

MODELLING THE DEAGGLOMERATION OF NANOPARTICLE INCLUSIONS BY ULTRASONIC MELT PROCESSING	1812
<i>Manoylov Anton, Lebon Bruno, Djambazov Georgi, Pericleous Koulis</i>	

WAVE PROPAGATION APPLICATIONS IN FLUIDS, COMPLEX SOLIDS AND STRUCTURES

ELASTIC WAVE PROPAGATION IN LIQUID FILLED BURIED PIPES	1820
<i>Kirby Ray, Duan Wenbo</i>	
ANALYSIS OF WAVE SCATTERING FROM NON-SYMMETRIC DISCONTINUITIES IN ONE-DIMENSIONAL WAVEGUIDES	1828
<i>Takiuti Breno, Lopes Junior Vicente, Brennan Michael, Manconi Elisabetta</i>	
WAVE PROPAGATION AND ATTENUATION IN AN INFINITE PERIODIC STRUCTURE OF ASYMMETRIC SCATTERERS	1836
<i>McMahon Darryl</i>	
DYNAMICS OF LONGITUDINALLY VIBRATING ROD WITH VARYING LENGTH AND CROSS SECTION	1844
<i>Shatalov Michael, Joubert Stephan, Fedotov Igor, Lekalakala Masodi, Bidie Judith</i>	
CONTROL OF TORSIONAL WAVES PROPAGATING IN A STRUCTURED BEAM.....	1850
<i>Sanchez-Dehesa Jose, Arreola-Lucas Arturo, Baez Gabriela, Cervera Francisco, Climente Alfonso, Mendez-Sanchez Rafael</i>	
WAVE PROPAGATION IN TUNABLE FLUID-FILLED BEAMS WITH SPATIALLY VARYING VISCOELASTIC PROPERTIES	1855
<i>Xu Hao, Wu Hong, Tan Songbin, Sui Fusheng</i>	
SCATTERING OF MULTIPLE SHALLOW-BURIED CAVITIES, INCLUSIONS AND FIXED SURFACE BY SH-WAVE IN ELASTIC SEMI-SPACE	1863
<i>Li Hongliang, Wang Yu, Tang Zhangzhou</i>	
RESEARCH ON DYNAMIC STRESS CONCENTRATION FACTOR AROUND THE HOLE UNDER PRIMARY WAVE	1870
<i>Pang Yuezhaoh, Jia Qu, Yang Lihong</i>	
STUDY ON TRANSMISSION CHARACTERISTICS OF MUD PULSE WAVES USED FOR TRANSMITTING INFORMATION FROM DOWNHOLE TO SURFACE IN DRILLING ENGINEERING	1878
<i>Gao Wenkai, Su Yinao, Shi Rong, Dou Xourong, Sheng Limin, Fan Jinhui</i>	
ANALYTICAL METHODS FOR ONE-DIMENSIONAL IMPACT PROBLEMS INVOLVING LAYERED ELASTIC MEDIA	1883
<i>Velo Ani P., Gazonas George A., Fouhy Aidan, Jayne Testerman</i>	
IMPACT RESPONSE OF A NONLINEAR VISCOELASTIC AUXETIC DOUBLY CURVED SHALLOW SHELL	1887
<i>Rossikhin Yury, Krusser Anastasia, Shitikova Marina</i>	

NONLINEAR ACOUSTICS AND VIBRATION

ON INVARIANT SOLUTIONS TO THE SECOND-ORDER EQUATION OF INVISCID GAS FLOW	1895
<i>Kozlov Alexander</i>	
NONLINEAR ACOUSTIC AND MAGNETOACOUSTIC WAVES IN MEDIA WITH ISENTROPIC INSTABILITY	1900
<i>Molevich Nonna, Zavershinskii Dmitrii, Ryashchikov Dmitrii, Zavershinskii Igor, Pichugin Sergei</i>	
NONLINEAR ACOUSTICS IN A GENERAL CURVED DUCT	1908
<i>McTavish James, Brambley Edward</i>	
INTERACTION OF NON-LINEAR NORMAL MODES OF A CANTILEVER BEAM	1915
<i>Hoskoti Lokanna, Misra Ajay, Sucheendran Mahesh</i>	
FREQUENCY ANALYSIS OF NONLINEAR STRUCTURES WITH UNCERTAINTIES PARAMETERS USING POLYNOMIAL CHAOS EXPANSION	1923
<i>Lamrhari Mohammed, Sarsri Driss, Azrar Lahcen, Rahmoune Miloud, Sbai Khalid</i>	
STUDY OF NONLINEAR PROPAGATION OF NOISE USING HIGHER-ORDER SPECTRAL ANALYSIS.....	1931
<i>Gurbatov Sergey, Demin Igor, Pronchatov-Rubtsov Nikolai</i>	

THE APPLICATION OF WIENER SERIES IN NONLINEAR RANDOM VIBRATIONS: AN ENHANCEMENT OF EQUIVALENT LINEARISATION	1938
<i>Demetriou Demetris, Langley Robin</i>	
A GENERAL METHOD FOR CALCULATING THE POWER DISSIPATED BY NONLINEAR OSCILLATORS DRIVEN BY RANDOM EXCITATION	1946
<i>Hawes David, Langley Robin</i>	
ON THE EVOLUTION OF THE INTENSE ACOUSTIC NOISE: THEORY AND EXPERIMENT	1954
<i>Gurbatov Sergey, Deryabin Mikhail, Kasyanov Dmitry, Kurin Vasily</i>	
BIFURCATION AND CHAOS OF A LINEAR STRUCTURE WITH A NONLINEAR ENERGY SINK	1962
<i>Chen Li-Qun, Zang Jian</i>	
FULLY SYNCHRONIZED ACOUSTOMECHANICAL TESTING OF SKIN: BIOMECHANICAL MEASUREMENTS OF NONCLASSICAL NONLINEAR PARAMETERS	1970
<i>Lints Martin, Santos Serge Dos, Kozena Colette, Kus Vaclav, Salupere Andrus</i>	
FESHBACH RESONANCE AND EXPLOSIVE INSTABILITY OF MAGNETOELASTIC WAVES.....	1978
<i>Preobrazhensky Vladimir, Aleshin Vladislav, Pernod Philippe</i>	
ON KHOKHLOV-ZABOLOTSKAYA-KUZNETSOV EQUATION AND SECOND-ORDER NONLINEAR GENERATION OF THE PARAMETRIC ACOUSTIC ARRAY	1986
<i>Farias Felipe, Abdulla Waleed</i>	
WAVE REFLECTION AT THE INTERFACE BETWEEN A NONLINEAR DISCRETE LATTICE AND A MATCHING LINEAR SYSTEM.....	1992
<i>Hoving Jeroen, Metrikine Andrei</i>	
ACOUSTIC STREAMING IN RESONATORS WITH HEATED WALLS.....	2000
<i>Cervenka Milan, Bednarik Michal</i>	
ACOUSTIC STREAMING IN RESONATOR OF SQUARE CROSS SECTION	2007
<i>Yano Takeru</i>	
SOME RESULTS ON A REVISITED BOUNCING BALL MODEL EXCITED BY A STATIONARY CONTINUOUS TIME CORRELATED STOCHASTIC PROCESS.....	2012
<i>Perret-Liaudet Joel, Zouabi Chaima, Scheibert Julien</i>	
 <u>SOUND PROPAGATION IN CURVILINEAR SPACETIME</u>	
NONLINEAR ACOUSTICS IN CURVILINEAR SPACETIME.....	2016
<i>Gan Woon Siong</i>	
AEROACOUSTIC DESIGN OF METAFUID DEVICES.....	2024
<i>Iemma Umberto, Palma Giorgio</i>	
 <u>THERMOACOUSTICS AND COMBINATION NOISE</u>	
INFLUENCE OF CALORICALLY PERFECT GAS ASSUMPTION AND THERMAL DIFFUSION ON INDIRECT NOISE GENERATION	2032
<i>Huet Maxime</i>	
ACCOUNTING FOR ACOUSTIC DAMPING IN A 3D HELMHOLTZ SOLVER	2040
<i>Ni Franchine, Miguel-Brebion Maxence, Nicoud Franck, Poinot Thierry</i>	
LOW ORDER MODELLING OF DIRECT AND INDIRECT COMBUSTION NOISE CONTRIBUTIONS IN A GAS TURBINE MODEL COMBUSTOR	2048
<i>Mahmoudi Yasser, Dowling Ann, Swaminathan Nedunchezian</i>	
ANALYTICAL SOLUTIONS OF THE ONE-DIMENSIONAL ACOUSTIC WAVES IN A DUCT	2056
<i>Jingxuan Li, Aimee Morgans</i>	
ROBUST FEEDBACK CONTROL OF THERMOACOUSTIC OSCILLATIONS	2064
<i>Orchini Alessandro, Illingworth Simon</i>	
PARAMETRIC SENSITIVITY ANALYSIS FOR PREMIXED SWIRLING M-FLAMES	2072
<i>Skene Calum, Schmid Peter</i>	
ACOUSTIC AND ENTROPIC TRANSFER FUNCTIONS OF A GENERALISED SUBSONIC NOZZLE	2080
<i>Domenico Francesca De, Rolland Erwan, Hochgreb Simone</i>	
ADVANCES IN THE MODELLING OF DISPERSION AND DIFFUSION OF ENTROPY WAVES IN GAS-TURBINE COMBUSTORS	2088
<i>Giusti Andrea</i>	
COMPOSITIONAL INHOMOGENEITIES AS A SOURCE OF INDIRECT COMBUSTION NOISE: PHYSICAL MECHANISMS AND FUEL EFFECTS.....	2096
<i>Ihme Matthias, O'Brien Jeffrey, Kim Jeonglae</i>	
SOUND GENERATED BY BLADES INTERACTING WITH ENTROPY WAVES	2104
<i>Inigo Juan Guzmán, Duran Ignacio, Morgans Aimee</i>	
LOW FREQUENCY GENERATION, TRANSMISSION AND REFLECTION OF DIRECT AND INDIRECT PERTURBATIONS THROUGH NOZZLES	2112
<i>Hochgreb Simone, Rolland Erwan O, Dedomenico Francesca De</i>	
COHERENCE RESONANCE IN A PREMIXED COMBUSTOR DRIVEN BY A TURBULENCE-INDUCED COLORED NOISE	2120
<i>Li Xinyan, Zhao Dan</i>	

ACTIVE CONTROL OF COMBUSTION INSTABILITIES USING AN ELECTROPNEUMATIC LOUDSPEAKER.....	2127
<i>Weng Fanglong, Zhou Shaowei, Makeximu, Zhu Min</i>	
TRANSITION TO TURBULENCE IN OSCILLATING FLOWS	2135
<i>Ramadan Islam, Abdel-Rahman Ehab, El-Rahman Ahmed I. Abd, Ibrahim A. H.</i>	
THE EFFECT OF THE POROSITY OF REGENERATORS ON THE PERFORMANCE OF A HEAT-DRIVEN THERMOACOUSTIC COOLER	2143
<i>Farikhah Irna, Ueda Yuki</i>	

THERMOACOUSTICS RESEARCH IN A GENDER-BALANCED SETTING

HEAT TRANSFER FROM A FLAT PLATE UNDER IMPINGING ACOUSTIC OSCILLATIONS	2151
<i>Robinson Nick, Lawn Chris</i>	
RECURRENCE ANALYSIS OF FORCED SYNCHRONIZATION IN A SELF-EXCITED THERMOACOUSTIC SYSTEM	2159
<i>Murugesan Meenatchidevi, Balusamy Saravanan, Hochgreb Simone, Li Larry K B</i>	
SENSITIVITY ANALYSIS OF THERMOACOUSTIC INSTABILITIES	2167
<i>Sogaro Francesca, Morgans Aimee, Schmid Peter</i>	
STABILIZATION OF SELF-SUSTAINED ACOUSTIC OSCILLATION USING HELMHOLTZ AND QUARTER WAVE RESONATORS	2175
<i>Bourquard Claire, Noiray Nicolas</i>	
COUPLED CFD-GREEN'S FUNCTION APPROACH FOR PREDICTION OF COMBUSTION INSTABILITIES IN GAS TURBINES	2183
<i>Bigongiari Alessandra, Heckl Maria, Iurashev Dmytro</i>	
OPTIMISING THE ACOUSTICS OF SHORT CIRCULAR HOLES WITH MEAN FLOW	2191
<i>Johnson Holly G., Morgans Aimee S.</i>	
PHASE SPACE DYNAMICS OF THERMOACOUSTIC INTERACTIONS DURING VORTEX ACOUSTIC LOCK-ON	2199
<i>Singh Gurpreet, Mariappan Sathesh, Singaravelu Balasubramanian</i>	
STABILITY ANALYSIS OF A MATRIX BURNER FLAME USING A GENERALISED HEAT RELEASE RATE LAW FEATURING MULTIPLE TIME-LAGS.....	2207
<i>Gopinathan Sreenath Malamal, Heckl Maria A.</i>	
LINEAR AND NONLINEAR STABILITY PREDICTIONS FOR A DOMESTIC BOILER WITH A HEAT EXCHANGER FOR PASSIVE INSTABILITY CONTROL.....	2215
<i>Surendran Aswathy, Heckl Maria A.</i>	
THE MARGINAL CONDITION FOR THE ONSET OF THERMOACOUSTIC OSCILLATIONS OF A GAS IN A TUBE HAVING A WET WALL POROUS MEDIUM.....	2223
<i>Ueda Yuki, Tsuda Kenichiro</i>	
EXPERIMENTAL INVESTIGATION OF ACOUSTIC STREAMING IN A SIMPLE THERMOACOUSTIC ENGINE	2227
<i>Ramadan Islam, Bailliet Helene, Valiere Jean-Christophe</i>	

COMBUSTION DYNAMICS AND ACOUSTICS IN GAS TURBINES AND FURNACE

EXPERIMENTAL RESEARCH OF ACOUSTIC-BASED FLAME SUPPRESSION FOR SPACE APPLICATION	2235
<i>Shi Yang, Chen Yong, Zhang Qiang, Chen Xiaoqian, Shi Hanyi, Gan Xiaohua, Yuan Bo</i>	
SIMULATING FLAME RESPONSE TO ACOUSTIC EXCITATION FOR AN INDUSTRIAL GAS TURBINE COMBUSTOR.....	2241
<i>Xia Yu, Morgans Aimee S., Jones William P., Han Xingsi</i>	
DAMPING DUE TO THE ACOUSTIC BOUNDARY LAYER IN HIGH FREQUENCY TRANSVERSE MODES	2249
<i>Romero Pedro, Hummel Tobias, Berger Frederik M., Schuermans Bruno, Sattelmayer Thomas</i>	
INFLUENCE OF DAMPERS ON THE DAMPING RATES OF A LAB SCALE ANNULAR COMBUSTOR	2257
<i>Betz Michael, Zahn Max, Sattelmayer Thomas</i>	

VOLUME 4

FREQUENCY DOMAIN PREDICTIONS OF THE ACOUSTIC REFLECTION COEFFICIENT OF A COMBUSTOR EXIT NOZZLE WITH LINEARIZED NAVIER-STOKES EQUATIONS	2265
<i>Zahn Max, Schulze Moritz, Hirsch Christoph, Wagner Michael, Sattelmayer Thomas</i>	
LARGE EDDY SIMULATIONS FOR THE FLAME DESCRIBING FUNCTION OF A PREMIXED TURBULENT SWIRLING FLAME.....	2273
<i>Laera Davide, Morgans Aimee S.</i>	
MODELING AND QUANTIFICATION OF ACOUSTIC DAMPING INDUCED BY VORTEX SHEDDING IN NON-COMPACT THERMOACOUSTIC SYSTEMS.....	2281
<i>Hummel Tobias, Hofmeister Thomas, Schuermans Bruno, Sattelmayer Thomas</i>	
IDENTIFICATION OF FLAME DISPLACEMENT FROM HIGH FREQUENCY THERMOACOUSTIC PULSATIONS IN GAS TURBINE COMBUSTORS.....	2289
<i>Berger Frederik M., Kaufmann Jan, Schuermans Bruno, Sattelmayer Thomas</i>	

USE OF FLAME TRANSFER FUNCTION TO PREDICT COMBUSTOR UNSTABLE MODES	2297
<i>Luciano Ennio, Tizné Eduardo, Ballester Javier</i>	

FLOW DUCT ACOUSTICS AND MUFFLERS

THREE-DIMENSIONAL ACOUSTIC ANALYSIS OF CONCENTRIC TUBE RESONATOR USING GREEN'S FUNCTION.....	2305
<i>Veerababu D., Venkatesham B.</i>	
EFFICIENT APPROACHES FOR THE ACOUSTIC MODELLING OF AUTOMOTIVE EXHAUST DEVICES. APPLICATION TO CONFIGURATIONS INCORPORATING GRANULAR MATERIALS AND MONOLITHS.....	2313
<i>Sánchez-Orgaz Eva M., Denia Francisco D., Martínez-Casas José, Baeza Luis</i>	
STUDIES ON FLOW GENERATED NOISE FROM CORRUGATED TUBES.....	2321
<i>Rajavel B., Prasad M.G.</i>	
THERMOVISCOUS DISSIPATION ON WAVE PROPAGATION IN CONICAL-CONFINED PIPELINE	2329
<i>Li Zheng, Chen Yong, Fan Chengguang, Shi Yang, Gan Xiaohua, Yuan Bo</i>	
DESIGN CURVES FOR ELBOW SILENCERS.....	2337
<i>Ramakrishnan Ramani, Shinbin Nicholas</i>	
NOISE ATTENUATION PERFORMANCE OF MULTIPLE HELMHOLTZ RESONATOR ARRAYS SYSTEM.....	2345
<i>Cai Chenzhi, Mak Cheuk Ming, Wang Xu, Chu Yi Jing</i>	
A SIMPLE NOVEL METHOD FOR DIRECT EVALUATION OF THE ACOUSTIC SOURCE IMPEDANCE OF THE EXHAUST SYSTEM OF A SINGLE CYLINDER ENGINE	2353
<i>Kumar K. M., Munjal M. L.</i>	
NUMERICAL PREDICTION OF PERFORATED TUBE ACOUSTIC IMPEDANCE	2361
<i>Pradeep G., Raja T. Thanigaivel, Veerababu D., Ganesan S., Venkatesham B.</i>	
VORTEX PULSATION SIMULATION OF A PIPING NOISE DAMPENER	2369
<i>Makaryants Georgy</i>	
SIMPLIFIED ONE-DIMENSIONAL MODEL FOR TRANSIENT TIME-DOMAIN SIMULATION OF CENTRIFUGAL PUMPS.....	2377
<i>Linkamp Andreas, Lehr Christian, Brümmer Andreas</i>	
STUDY ON ACOUSTIC ATTENUATION PERFORMANCE OF PERFORATED BRANCH TUBE SILENCER ATTACHED WITH THIN FIBER LAYER	2385
<i>Kang Zhongxu, Song Ruixiang, Zhang Lijuan, Wu Rui, Liu Qiang</i>	
DETECTION OF BOILING LIQUID LEVELS BY DECOMPOSITION OF ACOUSTIC WAVES MEASURED USING A WAVEGUIDE	2391
<i>Singh Sneha, Mohanty Amiya</i>	
VORTEX-SOUND INTERACTION FOR AN ANNULAR DUCT OPENING	2399
<i>Yang Dong, Morgans Aimee S., Luciano Ennio, Ballester Javier</i>	
COMPARATIVE ASSESSMENT OF ACOUSTIC EFFICIENCY OF MUFFLERS WITH DIFFERENT POROUS METALS.....	2407
<i>Igolkin Aleksandr, Safin Artur, Stadnik Dmitry, Almurzin Prokhor</i>	
THE STUDY ON MUFFLER PARAMETERS INFLUENCE ON THE PNEUMATIC PRESSURE REDUCING VALVE PERFORMANCE	2415
<i>Afanasev Kirill, Shakhmatov Evgeny, Igolkin Alexander, Stadnik Dmitry, Sverbilov Viktor</i>	

PIPE VIBRATION ANALYSIS AND MEASUREMENT

EXPERIMENTAL INVESTIGATION INTO ACOUSTIC CHARACTERISTICS OF LEAKAGE SIGNALS FROM UNDERWATER PLASTIC WATER-FILLED PIPES.....	2422
<i>Liu Bin, Gao Yan, Ma Yifan, Yang Jun</i>	
ON THE DISTINCTION OF AXISYMMETRIC WAVES WITHIN A FLUID-FILLED PIPE USING WAVENUMBER MEASUREMENT.....	2430
<i>Salimi Mohammadreza, Muggleton Jennifer, Rustighi Emiliano</i>	
INVESTIGATION INTO AN ADAPTIVE LEAK DETECTION METHOD IN WATER DISTRIBUTION PIPES	2437
<i>Ma Yifan, Gao Yan, Liu Bin, Yang Jun</i>	

OCCUPATIONAL AND ENVIRONMENTAL VIBRATION

VIBRATION CHARACTERISTICS OF CLOSED CABS BY ENERGY FINITE ELEMENT ANALYSIS	2445
<i>Niu Junchuan, Liu Zhihui</i>	
VIBRATION PERFORMANCE OF LONDON'S MILLENNIUM FOOTBRIDGE	2453
<i>Meinhardt Christian, Newland David, Talbot James, Taylor Douglas</i>	
WIND-RESISTANT AND SEISMIC DESIGN OF THIRD GENERATION NUCLEAR POWER ENGINEERING VNA SYSTEM	2461
<i>Han Mingjiang, Zhang Qichang, Hao Shuying, Dai Yingda</i>	
IMPROVED BLAST VIBRATION ANALYSIS USING THE WAVELET TRANSFORM.....	2469
<i>Ainalis Daniel, Ducarne Loïc, Kaufmann Olivier, Tshibangu Jean-Pierre, Verlinden Olivier, Kouroussis Georges</i>	

ANALYSIS OF 3RD OCTAVE BAND GROUND MOTIONS TRANSMISSION IN SYNCHROTRON RADIATION FACILITY SOLARIS	2477
<i>Ziemianski Daniel, Nowak Marcin, Kozien Marek</i>	

OCCUPATIONAL AND ENVIRONMENTAL NOISE

A FINITE-ELEMENT MODEL TO PREDICT INCIDENCE DE-PENDENT AND DIFFUSE FIELD NOISE REDUCTION BASED ATTENUATION OF EARMUFFS	2483
<i>Sgard Franck, Nélisse Hugues, Benacchio Simon, Doutres Olivier, Padois Thomas, Gaudreau Marc-André</i>	
THE THEORY OF A LOW-NOISE POWER FACILITY	2491
<i>Tupov Vladimir</i>	
SOLUTIONS FOR LOW-NOISE POWER FACILITY	2497
<i>Tupov Vladimir, Tupov Boris</i>	
ACOUSTIC INTERNET-OF-THINGS: LOW-COST, DISTRIBUTED, SYNCHRONOUS MEASUREMENT SYSTEMS FOR AUTOMATED SOUND SOURCE LOCALIZATION IN WIND PARKS AND WIND TURBINES	2505
<i>Wenzel Tobias, Rokita Dagmar, Ueberle Friedrich, Rettig Rasmus</i>	

CONTROL OF NOISE AND VIBRATION IN THE WORKPLACE

THE TRANSMISSION OF VIBROACOUSTIC ENERGY FROM THE INDUSTRIAL MACHINES THROUGH THE BUILDING STRUCTURE TO THE MOUNTING BASE	2513
<i>Ziaran Stanislav, Chlebo Ondrej</i>	
PREDICTION OF VIBRATION AND NOISE FROM PIPES AND CAVITIES WITH INTERNAL PRESSURE PULSATATIONS	2521
<i>Liu Jin</i>	
INVESTIGATIONS ON AIRBORNE ULTRASOUND AT WORKING PLACES	2529
<i>Kling Christoph, Schoeneweiss Robert, Wolff Andrea, Ullisch Christian</i>	
NOISE MITIGATION AND ATTENUATION FOR TEST CELL WITH MULTIPLE SMALL ENGINES	2533
<i>Evans Jack B</i>	
PREDICTION OF TOOL-SPECIFIC GLOVE ATTENUATION PERFORMANCE IN REAL WORKPLACE	2541
<i>Shibata Nobuyuki</i>	
NOISE BARRIER AT WELDING WORKPLACE	2546
<i>Piechowicz Janusz, Piechowicz Jakub</i>	
NOISE TESTING METHODOLOGY IN THE PACKAGING INDUSTRY	2553
<i>Smagowska Bozena, Pleban Dariusz</i>	
OPTIMAL DESIGN OF HYDRAULIC DYNAMIC ANTI-RESONANCE ISOLATORS FOR TUNING OF THE ISOLATION FREQUENCY RANGE	2559
<i>Dong Xingjian, Xiao Han, Peng Zhike, Meng Guang</i>	
THE RESEARCH ON THE NOISE CONTROL OPTIMIZATION SCHEME OF THE 110KV NEW GENERATION SMART SUBSTATION	2567
<i>Hu Sheng, Wu Xiaozhong, Ouyang Lifan</i>	
WORKPLACES IN WIND FARMS AND IN THEIR VICINITY – RECOMMENDATIONS FOR WIND TURBINE NOISE REDUCTION	2575
<i>Pleban Dariusz, Radosz Jan, Smagowska Bozena</i>	

ENVIRONMENTAL NOISE AND VIBRATION CONTROL IN SMALL, MEDIUM AND LARGE INDUSTRIES

ENVIRONMENTAL NOISE AND VIBRATION CONTROL OF INDUSTRIES: CASE STUDIES	2581
<i>Asselineau Marc, Gaulupeau Aline</i>	
DEMONSTRATION OF BEST AVAILABLE TECHNIQUES AND APPROPRIATE MEASURES FOR THE PERMITTING AND REGULATION OF INDUSTRY	2585
<i>Clayton Tony, Tofts Jon, Waddington David</i>	
ENVIRONMENTAL NOISE AND GROUND BORNE VIBRATION CONTROL FOR A PRECISION CALIBRATION LABORATORY	2591
<i>Evans Jack B</i>	
DESIGN OF NOISE CONTROL TECHNOLOGY IN SUBSTATIONS AND CONVERTER STATIONS	2599
<i>Hu Sheng, Chen Shaoyi, Wu Xiaowen, Yang Jinchun, Peng Jiwen, Li Tienan, Xie Yine, Tang Qi</i>	

CONDITION MONITORING AND VIBRATION TESTING

FAULT DETECTION OF ROLLING BEARINGS USING AN ENSEMBLE AVERAGE AUTOCORRELATION BASED STOCHASTIC SUBSPACE IDENTIFICATION	2607
<i>Xu Yuandong, Li Haiyang, Zhen Dong, Rehab Ibrahim, Gu Fengshou, Ball Andrew</i>	
MONITORING AND DETECTING BALL BEARING FAULTS	2615
<i>Notohardjono Budy, Cruz Ethan, Chernega Gary, Zhang Jing</i>	

EXTREME LEARNING MACHINE AND DECISION TREE BASED ENSEMBLE TECHNIQUES FOR DIAGNOSIS OF ROLLING ELEMENT BEARING DEFECTS	2623
<i>Upadhyay Nitin, Kankar Pavan Kumar</i>	
RESEARCH ON THE DYNAMIC BEHAVIOUR OF FLEXIBLE CONNECTION ROTOR SYSTEM UNDER SEISMIC EXCITATION	2631
<i>Gao Fei, Zuo Jianli, Wang Hairong, Wang Wencai</i>	
IDENTIFICATION OF DAMPED FOUNDATIONS IN ROTATING MACHINERY	2639
<i>Feng Ningsheng, Hahn Eric, Yu Minli</i>	
BALANCING ON THE VERTICAL SHAFT OF A FLYWHEEL ENERGY STORAGE SYSTEM.....	2647
<i>Dai Xingjian, Li Xi, Zhang Kai, Liu Pei</i>	
DETECTION OF UNBALANCE IN A ROTOR-BEARING SYSTEM USING A DETERMINISTIC-STOCHASTIC APPROACH	2654
<i>Shrivastava Akash, Mohanty Amiya</i>	
USE OF MECHANICAL RESONANCE IN MACHINES DRIVE SYSTEMS	2661
<i>Fiebig Wieslaw, Wróbel Jakub</i>	
AEROELASTICITY OF A ROTATING BLADE COUPLED WITH A NONLINEAR ENERGY SINK	2669
<i>Guo Hulun, Cao Shuqian, Chen Yushu</i>	
THE HARDEST MODE OF BROADBAND RANDOM VIBRATION ON THE OWN SPECTRUM BANDS OF MECHANICAL SYSTEMS	2677
<i>Ovchinnikov Igor N.</i>	
MECHANICAL SHOCK SHAPE CALCULATION FROM ESTIMATED ACCELEROMETER PARAMETERS.....	2684
<i>Kunz Jan, Benes Petr</i>	
CONDITION MONITORING OF GEARS UNDER MEDIUM ROTATIONAL SPEED	2690
<i>Mauricio Alexandre, Freitas Carina, Cuenca Jaques, Hendrickx Kilian, Gryllias Konstantinos, Cornelis Bram, Janssens Karl</i>	
MULTISCALE SPECTRAL SUBTRACTION METHOD AND SUPPORT VECTOR MACHINE FOR CLUSTERING HEAVY BACKGROUND NOISE CLASSIFICATION	2698
<i>Tsai Yu-Ting, Huang Jin H.</i>	
VIBRATION OF VERY LARGE SHIP EXCITED BY MAIN ENGINE	2704
<i>Zhang Xiao, Li Zhaohui, Wang Hao, Yang Hezhen</i>	
NOVEL VIBRATION DIAGNOSIS TECHNOLOGY FOR INDUSTRIAL GEARBOXES	2709
<i>Gelman Len, Chandra Harish, Patel Mahesh, Manning-Ohren David</i>	
 <u>FAULT DIAGNOSIS AND PROGNOSIS</u>	
DYNAMIC CHARACTERISTICS ANALYSIS OF DISK-COUPLING-SHAFT SYSTEM CONSIDERING DISK ECCENTRICITY AND DISTORTION OF COUPLING	2715
<i>Wang Yu, Hongliang Li</i>	
EFFECT OF PISTON WIND ON FAULT DIAGNOSIS OF UNDERGROUND TUNNEL FAN.....	2723
<i>Song Yongxing, Chu Ning, Yu Siqi, Yang Shuai, Wu Dazhuan</i>	
EFFECT OF THERMAL ENVIRONMENT ON VIBRATION ANALYSIS OF ISOTROPIC MICRO PLATE WITH INCLINED CRACK BASED ON MODIFIED COUPLE STRESS THEORY	2731
<i>Gupta Ankur, Jain N.K., Salhotra R., Joshi P.V.</i>	
A COMBINED VIBRATION-BASED CONDITION MONITORING AND FINITE ELEMENT ANALYSIS APPROACH FOR FAILURE ASSESMENT OF ANNULAR GAS SCRUBBING SYSTEMS	2738
<i>Alderete Nicolas, Echaniz Gonzalo, Larco Federico</i>	
EVALUATION OF LEAD COATED BALL BEARING USING FREQUENCY ANALYSIS IN EXTREME CONDITIONS	2746
<i>Lee YongBok, Kwak Wonil, Choe BokSeong</i>	
INDICATIVE BEARING FAULT ANALYSIS OF WIND TURBINE GENERATOR BEARING USING TOWER VIBRATION	2750
<i>Mollasalehi Ehsan, Wood David, Sun Qiao</i>	
COULD AN ARRAY OF MEMS MICROPHONES BE USED TO MONITOR MACHINERY CONDITION OR DIAGNOSE FAILURES?	2758
<i>del-Val Lara, Izquierdo Alberto, Villacorta Juan José, Suarez Luis, Herráez Marta</i>	
A TWO STAGE KALMAN FILTERING APPROACH FOR REAL TIME DAMAGE DETECTION FROM VIBRATION RESPONSE OF A STRUCTURE USING MINIMUM NUMBER OF MEASUREMENTS.....	2766
<i>Sunny Mohammed Rabius</i>	
 <u>MACHINERY HEALTH MONITORING</u>	
NUMERICAL SIMULATION OF ONE-STAGE GEARBOX DYNAMICS IN THE PRESENCE OF SIMULTANEOUS TOOTH CRACKS.....	2774
<i>Mohamed Ahmed, Sassi Sadok, Roshun Mohammad</i>	
STRUCTURAL DAMAGE DETECTION USING DISTURBED PARTICLE SWARM OPTIMIZATION	2782
<i>Wei Zitian, Huang Jialu, Lv Zhongrong, Wu Wenwei</i>	
COMPARATIVE STUDY ON DETECTION OF INCLINED EDGE CRACK USING STATIC DEFLECTION MEASUREMENTS AND NATURAL FREQUENCIES	2790
<i>Naik Sachin, Pansare Sunil</i>	

EVALUATING SIGNAL PROCESSING METHODS FOR USE IN GEARBOX CONDITION MONITORING.....	2797
<i>Fromberger Max, Weinberger Max, Kohn Bernhard, Utakapan Thanak, Otto Michael, Stahl Karsten</i>	
EFFECT OF PITTING ON EXCITATION BEHAVIOUR OF A PLANETARY GEAR SET WITH SEQUENTIAL MESH PHASING.....	2805
<i>Weinberger Uwe, Fromberger Max, Kohn Bernhard, Otto Michael, Stahl Karsten</i>	
DIESEL AND GAS ENGINES DIAGNOSIS BASED ON INSTANTANEOUS ANGULAR SPEED ANALYSIS	2813
<i>Saiah Hamid, Clement Jean-Christophe</i>	

VIBRATION-BASED CONDITION MONITORING WITH END-OF-LINE TESTING

RESEARCH ON DYNAMIC MODELING AND VIBRATION CHARACTERISTICS OF RIGID-FLEXIBLE COUPLING ROTATING BLADE.....	2821
<i>Yang Yaliu, Guangcai Han</i>	
INVESTIGATION AND IMPROVEMENT OF FLOOR IMPACT SOUND INSULATION IN CHINA.....	2829
<i>Zhang Yiqing, Zhang Sanming, Wang Fangying, Chen Linbing</i>	
HEAVY DUTY ENGINE MOUNT ADDING WITH SENSITIVITY ANALYSIS APPROACH.....	2834
<i>Ayaz Hakan, Cetin Alp, Tabak Selcuk</i>	

QUIET MACHINE DESIGN

IN-PLANE AND BENDING VIBRATION ANALYSIS OF A DOUBLE BOTTOM CABIN USING DYNAMIC STIFFNESS METHOD	2842
<i>Li Hui, Wu Wenwei, Yin Xuewen</i>	
A CASE STUDY OF THRUST VARIATION FORCE DUE TO AXIAL AND TORSIONAL VIBRATION ON TWO STROKE LOW SPEED DIESEL ENGINES.....	2850
<i>Lee Donchool, Kim Sang-Hoon, Barro Ronald D</i>	
AN INTAKE SILENCER FOR THE CONTROL OF MARINE DIESEL TURBOCHARGER COMPRESSOR NOISE	2858
<i>Liu Chen, Cao Yipeng, Shen Hua, Zhang Wenping, Zhao Xiaochen</i>	
ACOUSTIC DESIGN OF A BEST-IN-CLASS DRILL RIG CABIN	2866
<i>Tanttari Jukka, Lamula Lasse</i>	
REDUCING AIRBORNE SOUND RADIATION FROM MACHINE STRUCTURES	2874
<i>Pathan Shah Nawaz Khan, Manik Dhanesh</i>	
TOPOLOGY OPTIMIZATION APPROACH OF DAMPING TREATMENT IN CABIN ACOUSTIC DESIGN	2882
<i>Zhang Jianrun, Sun Beibei, Lu Xi</i>	
THE EFFECTS OF DIFFERENT RUBBER TRACKS ON NOISE AND VIBRATION LEVELS AT THE OPERATOR STATION OF A TRACKED OFF-ROAD MACHINE	2890
<i>Miccoli Giuseppe, Carletti Eleonora</i>	
NOISE CLASSES FOR THE OUTDOOR MACHINES SUBJECT TO NOISE LIMITS	2898
<i>Carletti Eleonora, Pedrielli Francesca</i>	
OPERATIONAL TRANSFER PATH ANALYSIS OF A WASHING MACHINE	2906
<i>Tutu Gurkan, Uslu Ahmet Ali, Sanliturk Kenan Y.</i>	
DESIGN OF WAVEGUIDE VIBRATION ABSORBER WITH GROOVED CIRCULAR DISK FOR REDUCING REFRIGERATOR VIBRATION AND NOISE.....	2914
<i>Lei Ye, Wang Haitao, Zeng Xiangyang, Liu Yanshan, Du Bokai</i>	
ACOUSTIC AND ENERGY EFFICIENCY ANALYSIS OF POLYMER ROTOR APPLICATION IN A GEAR MICROPUMP	2922
<i>Rodionov Leonid, Rekadze Pavel, Gafurov Salimzhan</i>	
GEAR MESH RESONANCE AND STIFFNESS VALIDATED IN CALCULATION AND EXPERIMENT	2930
<i>Otto Michael, Fromberger Maximilian, Stahl Karsten</i>	
DESIGN OF LOW NOISE MICRO GEOMETRIES FOR HELICAL GEARS ON THE BASIS OF TRANSMISSION ERROR UNDER LOAD.....	2938
<i>Kohn Bernhard, Fromberger Maximilian, Weinberger Uwe, Utakapan Thanak, Otto Michael, Stahl Karsten</i>	
AN EMPIRICAL MODE DECOMPOSITION-INDEPENDENT COMPONENT ANALYSIS BASED APPROACH FOR DETECTING LOCALIZED AND DISTRIBUTED FAULTS IN ROLLING BEARING DIAGNOSTICS	2946
<i>Martarelli Milena, Chiariotti Paolo, Castellini Paolo, Sereni Alessandro, Tomasini Enrico Primo</i>	
RECENT DEVELOPMENTS IN THE DESIGN OF CENTRIFUGAL PENDULUM VIBRATION ABSORBERS	2954
<i>Newland David</i>	
THE LONGITUDINAL VIBRATION OF COMPOSITE DRIVE SHAFT.....	2962
<i>Zhang Tongtong, Li Yongsheng, Wang Weibo</i>	
RESEARCH ON THE EQUILIBRIUM PERFORMANCE OF FRAMEWORK LAYER OF PNEUMATIC VIBRATION ISOLATOR.....	2970
<i>Zhao Yinglong, Jin Zhu, Liu Jian, Zhu Haichao</i>	

MACHINE TOOL VIBRATION AND CUTTING DYNAMICS

THREE-DIMENSIONAL VIBRATION ANALYSIS FOR ONLINE MONITORING OF MILLING PROCESS AND SPINDLE BEARINGS	2977
<i>Bisu Claudiu, Zapciu Miron</i>	
THE EFFECT OF TIME DELAY VARIATION INDUCED BY WORKPIECE EXCITATION ON REGENERATIVE CHATTER IN MILLING.....	2985
<i>Nakano Yutaka, Takahara Hiroki, Akiyama Yu</i>	
OPTIMAL SPINDLE SPEED MACHINING BASED ON ADAPTIVE STABILITY ANALYSIS.....	2993
<i>Cheng Chih-Chun, Cheng Yin-Chung, Chiu Yu-Sheng, Cheng Wen-Nan, Tsai Ping-Chun, Sung Cheng-Kuo</i>	
DYNAMICS OF MILLING THIN-WALLED STRUCTURE.....	3001
<i>Ren Song, Jiao Sujuan, Chen Yong, Long Xinhua</i>	

FLUID MACHINERY NOISE

NEW CRITERIA INVESTIGATION ON THE LUBRICATION STATES TRANSITION FOR WATER LUBRICATED PLAIN JOURNAL BEARING	3009
<i>Xie Zhongliang, Rao Zhushi, Ta Na, Zou Fen, Jiao Chunxiao</i>	
CORRECTING FREQUENCY CHARACTERISTICS OF PRESSURE PULSATIONS PROBES (REVIEW)	3015
<i>Gimadiev Asgat, Bystrov Nikolay, Gimadiev Marat, Stadnik Dmitry, Igolkin Alexander</i>	
EXPERIMENTAL STUDY ON THE PUMP ACOUSTIC SOURCE CHARACTERIZATION BASED ON THE TWO PORT MODEL	3023
<i>Xuan Ling-Kuan, Pan Ya-Jun, Yuan Xing-Jun, Ruan Zhu-Qing, Wang Guan</i>	

VOLUME 5

A FAST PREDICTION METHOD OF ACOUSTIC RADIATION FROM ELASTIC CYLINDRICAL SHELL IN SHALLOW WATER	3029
<i>Chen Hongyang, Li Qi, Shang Dejiang, Wang Hao</i>	

TRANSFER PATH ANALYSIS IN NVH ENGINEERING

ON NUMERICAL ANALYSIS AND EXPERIMENT VERIFICATION OF CHARACTERISTIC FREQUENCY OF ANGULAR CONTACT BALL-BEARING IN HIGH SPEED SPINDLE SYSTEM	3037
<i>Wu T. Y., Sun C. C., Chen Y. C.</i>	
POST CORRECTING FOR GYROSCOPIC EFFECTS VIA DYNAMIC SUBSTRUCTURING	3045
<i>Haeussler Michael, Reichart Ron, Bartl Andreas, Rixen Daniel</i>	
THE IN-SITU DECOUPLING OF RESILIENTLY COUPLED SUB-STRUCTURES.....	3053
<i>Meggitt Joshua, Moorhouse Andy</i>	
USING MEASURED BLOCKED FORCES TO PROVIDE REALISTIC EXCITATION OF VIRTUAL ACOUSTIC PROTOTYPES.....	3061
<i>Moorhouse Andy, Meggitt Joshua, Elliott Andy</i>	
A BENCHMARK STRUCTURE FOR VALIDATION OF BLOCKED FORCE TRANSFER PATH ANALYSIS TECHNIQUES	3069
<i>Pasma Eric, Seijs Maarten van der, Bosch Daniël van den, Wernsen Mathieu</i>	
CONTRIBUTION ANALYSIS OF VEHICLE BODY VIBRATION MODE TO THE INTERIOR NOISE UTILIZING OPERATIONAL TPA	3077
<i>Yoshida Junji, Hayashi Daiki, Kajiyama Takuya</i>	
INTERNAL TRANSFER PATH ANALYSIS BASED ON IN-SITU BLOCKED FORCES AND TRANSMISSIBILITY FUNCTIONS	3085
<i>Zabel Dennis, Sturm Michael, Moorhouse Andy, Alber Thomas</i>	
APPLICATIONS OF THE ROUND TRIP THEORY FOR THE INDIRECT MEASUREMENT OF POINT IMPEDANCE BY AIRBORNE EXCITATION	3093
<i>Elliott Andrew, Moorhouse Andy</i>	
A FRAMEWORK FOR SENSITIVITY ANALYSIS OF TRANSFER PATHS COMBINING CONTRIBUTION ANALYSIS AND RESPONSE MODIFICATION ANALYSIS	3100
<i>Arsic Dejan, Pohl Matthias</i>	
EXPERIMENTAL NUMERICAL CORRELATION OF SUBSYSTEM CONTRIBUTIONS IN THE ADVANCED TRANSFER PATH ANALYSIS FRAMEWORK.....	3108
<i>Magrans F X, Poblet-Puig J, Arcas K, Rodriguez P V, Rodriguez-Ferran A</i>	

SOUND ABSORPTION MATERIALS

HELMHOLTZ RESONATORS SYSTEMS TREATED WITH THE NANOFIBROUS MEMBRANE	3116
<i>Ulrich Tomáš, Kalinová Klára</i>	
EXPERIMENTAL INVESTIGATION OF SOUND ABSORPTION OF LOOSE BIO-SOURCED ALFA FIBERS	3124
<i>Boushine Said, Boubel Ayoub, Garoum Mohammed, Ammar Adil</i>	

EXPERIMENTAL INVESTIGATION OF SOUND ABSORPTION OF SOME LOOSE UNCOOKED GRANULAR PASTAS, STARCHY FOODS AND CEREALS	3130
<i>Boubel Ayoub, Bousshine Said, Garoum Mohammed, Ammar Adil</i>	
ACOUSTICAL EDUCATION OF POROUS MEDIA PROPERTIES	3136
<i>Roncen Remi, Simon Frank, Piot Estelle</i>	
ESTIMATION OF ACOUSTIC PROPERTIES FOR POROUS MATERIAL WITH SURFACE ACOUSTIC IMPEDANCE.....	3144
<i>Kim Bo-Seung, Park Junhong</i>	
SOUND ABSORBING PERFORMANCE OPTIMIZATION BASED ON CHARACTERISTIC IMPEDANCE	3147
<i>Huang Zhehao, Wang Xiaolin</i>	
RESEARCH ON EXPERIMENTAL SOUND ABSORPTION PERFORMANCE UNDER HIGH TEMPERATURE AND HIGH SOUND INTENSITY COUPLING CONDITIONS	3155
<i>Wang Xiaopeng, Du Xiaowen, Xi Yanhui, Chen Tianning, Niu Chunping</i>	
LONG ELASTIC OPEN NECK ACOUSTIC RESONATOR FOR WIDE FREQUENCY RANGE	3163
<i>Simon Frank, Sebbane Delphine</i>	
UTILIZATION OF SOUND PATH DIFFERENCE TO FURTHER ENHANCE LOW FREQUENCY SOUND ABSORPTION PERFORMANCE OF THE PERFORATED PANEL RESONATOR WITH FLEXIBLE TUBE BUNDLES	3171
<i>Lyu Yadong, Xie Hai, Zhang Chun</i>	
EFFECTS OF PORE-SIZE DISTRIBUTION ON SOUND ABSORPTION OF MATERIAL FABRICATED BY ADDITIVE MANUFACTURING	3177
<i>Wang Xiaolin, Liang Hao</i>	

ACOUSTIC MATERIALS

RECENT DEVELOPMENTS IN THE ACOUSTICAL PROPERTIES OF PERFORATED AND POROUS MATERIALS CONTAINING DEAD-END PORES – APPLICATIONS TO LOW FREQUENCY SOUND ABSORPTION.....	3184
<i>Leclaire Philippe, Lardeau Alexandre, Dupont Thomas, Geslain Alan, Panneton Raymond, Brooke Daniel, Umnova Olga</i>	
MACROMECHANICAL MODELLING OF ELASTIC AND VISCO-ELASTIC COSSERAT CONTINUUM AND WAVES FORMATION IN A SUCH A MEDIUM	3192
<i>Malkhanov Alexey O., Erofeev Vladimir I.</i>	
COMPARISON OF POOL ISOLATION SYSTEMS.....	3200
<i>Murray Timothy, Cosstick Lloyd, Hong Evan, Hall Gary</i>	
STUDY ON THE PRODUCIBILITY OF ADDITIVELY MANUFACTURED ACOUSTIC BLACK HOLES	3208
<i>Rothe Sebastian, Watschke Hagen, Langer Sabine C.</i>	
EFFECTIVE PARAMETER IDENTIFICATION AND CONTROLLER DESIGN FOR ACTIVE MECHANICAL METAMATERIALS.....	3216
<i>Pope Simon</i>	
DESIGN OF MICRO STRUCTURE OF POROELASTIC MATERIAL TO CONTROL SOUND ABSORPTION BY HOMOGENIZATION METHOD	3224
<i>Yamamoto Takashi, Imae Yuki</i>	
EFFECT OF THE POROUS MATERIAL MODELING ON THE EXTERNAL SOUND FIELD	3231
<i>Napolitano Marialuisa, Dragonetti Raffaele, Romano Rosario, Di Filippo Sabato</i>	
THERMAL ANALYSIS FOR HIGH TEMPERATURE SOUND ABSORBING APPARATUS OF POROUS METALS	3238
<i>Zhang Bo, Zhang Junzhe, Rejab Mohd Ruzaimi Mat</i>	
VIBRATION ANALYSIS OF DOUBLE-DECK SANDWICH PLATES WITH LATTICE CORES	3244
<i>Guo Zhenkun, Li Fengming</i>	
AN IMPLICIT TIME-DOMAIN FINITE ELEMENT SCHEME FOR SOUND FIELD ANALYSIS WITH PERMEABLE MEMBRANE ABSORBERS	3251
<i>Okuzono Takeshi, Sakagami Kimihiro, Akihiro Katsuyama</i>	

DAMPING MATERIALS

OPTIMIZING THE MECHANICAL CHARACTERIZATION OF A RESILIENT INTERLAYER FOR THE USE IN TIMBER CONSTRUCTION.....	3259
<i>Barbaresi Luca, Morandi Federica, Belcari Juri, Zucchelli Andrea, Speranza Alice</i>	
MODELLING METHOD AND VIBRATION REDUCTION OPTIMIZATION FOR PERIODIC MASS-SPRING AUXETIC CELLULAR MOUNT	3266
<i>Qin Haoxing, Yang Deqing</i>	
A GENERAL THEORY FOR LAYERED THICK SHELL OF A MAGNETORHEOLOGICAL FLUID CORE.....	3273
<i>Huang Shyh-Chin, Tsai Chao-Yang</i>	
ELASTIC AND VISCOELASTIC PROPERTIES OF SYNTHETIC RUBBER (POLYCHLOROPRENE): DYNAMIC AND STATIC CHARACTERIZATION	3281
<i>Schiavi Alessandro, Prato Andrea</i>	
DESIGNING OF VIBRATION ISOLATING METAMATERIAL WITH QUASI-ZERO EFFECT	3289
<i>Anvar Valeev</i>	

VIBRO-ACOUSTIC RESPONSE OF A TURBOPROP CABIN WITH INNOVATIVE SIDEWALL VISCOELASTIC TREATMENT	3296
<i>Massimo Viscardi, Maurizio Arena</i>	
NONLINEAR VIBRATIONAL ANALYSIS OF THIN RECTANGULAR MAGNETO-ELECTRO-ELASTIC COMPOSITE MATERIAL BY PERTURBATION TECHNIQUES	3304
<i>Roknizadeh Seyed Alireza Seyed, Amanieh Hamidreza Talebi, Marashi Seyed Mehdi Ghazi</i>	
DYNAMIC PROPERTIES OF EPOXIDISED NATURAL RUBBER	3312
<i>Rahim Mahmud Iskandar Seth A., Horoshenkov Kirill, Rongong Jem, Ahmadi Hamid, Picken Judith</i>	
PHYSICAL PROPERTIES OF RESILIENT MATERIALS FOR FLOOR IMPACT SOUND REDUCTION	3319
<i>Kim Kyoung Woo, Shin Hye Kyung, Jeong A Yeong, Yang Kwan Seop</i>	
DESIGN AND FABRICATING OF LIGHT WEIGHT VIBROISOLATING SYSTEM WITH REQUIRED FILTERING PROPERTIES	3324
<i>Tomilina Tatiana, Sotov Anton, Grebennikov Alexander, Laktionova Maria</i>	
ASSESSMENT METHOD OF VIBRATION REDUCTION OF DAMPING MATERIAL BASED ON MODE ANALYSIS	3328
<i>Ruan Zhuqing Ruan, Dong Wanjing, Xuan Lingkuan, Pan Yajun, Zhang Qi</i>	

ACOUSTIC METAMATERIALS AND PHONONIC CRYSTALS: FUNDAMENTALS AND APPLICATIONS

LOW FREQUENCY ACOUSTIC PROPERTIES OF A HONEYCOMB-SILICONE RUBBER ACOUSTIC METAMATERIAL	3335
<i>Gao Nansha, Hou Hong</i>	
NUMERICAL INVESTIGATIONS OF MEMBRANE-TYPE ACOUSTIC METAMATERIALS WITH ECCENTRIC MASSES FOR BROADBAND SOUND ISOLATION	3343
<i>Lau Siu-Kit, Lu Zhenbo, Lim Kah Hsien, Liu Yiyuan, Khoo Boo Cheong, Yu Xiang</i>	
FLUID CONTROL BY ACOUSTIC META-LENS ARRAY	3350
<i>Kim Sang-Hoon</i>	
QUANTUM PHONONIC CRYSTAL	3354
<i>Gan Woon Siong</i>	
ACOUSTIC CLOAK IN THE PRESENCE OF COMPRESSIBLE NON-UNIFORM MEAN FLOW	3362
<i>Ryoo Hyeonbin, Jeon Wonju</i>	
PARAMETRIC STUDY OF CONTROL OF FREQUENCY BANDED BEHAVIOUR OF PRESSURISED COMPOSITE STRUCTURES	3366
<i>Ampatzidis Theofanis, Chronopoulos Dimitrios</i>	
EXAMINATION OF ACOUSTIC INSULATION OF COMPOSITE METAMATERIALS WITH NEGATIVE STIFFNESS ELEMENTS INCLUSIONS	3373
<i>Ampatzidis Theofanis, Chronopoulos Dimitrios, Antoniadis Ioannis</i>	
EXPERIMENTAL ANALYSES OF A MEMBRANE TYPE SOUND ABSORBER WITH MAGNETIC NEGATIVE STIFFNESS	3381
<i>Zhao Junjuan, Li Xianhui, Wang Yueyue, Wang Wenjiang, Zhang Bin</i>	
BROADBAND ASYMMETRIC ACOUSTIC TRANSMISSION BASED ON AN ACOUSTIC PRISM AND ABSORPTIVE MATERIAL	3386
<i>Song Ailing, Chen Tianning, Wang Xiaopeng</i>	
DESIGN OF FLEXURAL WAVES WAVEGUIDE BASED ON FINITE EMBEDDED COORDINATE TRANSFORMATION THEORY	3393
<i>Chen Xing, Cai Li, Wen Jihong, Yang Haibin</i>	
THE EFFECT OF COORDINATE TRANSFORMATION FUNCTION ON SCATTERING CHARACTERISTICS OF LAYERED CYLINDRICAL PENTAMODE ACOUSTIC CLOAK	3399
<i>Cai Li, Wen Jihong, Yu Dianlong, Chen Xing, Lu Zhimiao</i>	
A LOW-FREQUENCY METASURFACE ABSORBER BASED ON HELMHOLTZ RESONATORS	3406
<i>Zhao Honggang, Wang Yang, Zhao Dan, Wen Jihong, Lam Yiu Wai, Umnova Olga</i>	
METAMATERIAL PANEL WITH ARRAYS OF PIEZOELECTRIC PATCHES CONNECTED TO MULTI-RESONANT ELECTRICAL SHUNTS	3414
<i>Zientek Michal, Gardonio Paolo</i>	
NOISE REDUCTION AND HEAT-DISSIPATING OF REFRIGERATORS BY USING PERFORATED ACOUSTIC METAMATERIALS	3422
<i>Wang Wei, Wang Xiaole, Huang Zhenyu, Fan Qiang</i>	
STRONG ANOMALOUS SCATTERING OF SOUND AT A LINEAR CHAIN OF PERFORATED CYLINDERS	3429
<i>Krokhin Arkadii, Bozhko Andrey, Cervera Francisco, Sanchez-Dehesa Jose</i>	
NUMERICAL MODELS OF SINGLE- AND DOUBLE-NEGATIVE METAMATERIALS INCLUDING VISCOUS AND THERMAL LOSSES	3434
<i>Henriquez Vicente Cutanda, Sanchez-Dehesa Jose</i>	
INVESTIGATION OF ELLIPTICAL SONIC METAMATERIALS	3441
<i>Xuhong Miao, Shuo Li, Xueren Wang, Fuzhen Pang</i>	
VIBRATION BAND GAPS OF ONE-DIMENSIONAL PHONONIC CRYSTALS USING WAVE FINITE ELEMENT METHOD	3449
<i>Wu Hong, Xu Hao, Sui Fusheng, Bai Guofeng</i>	
IMPEDANCE DESIGN OF EFFICIENT METAMATERIAL SOUND ABSORBERS	3457
<i>Tomilina Tatiana, Bobrovnikii Yuri, Bakhtin Boris, Safin Artur, Afanasev Kirill</i>	

SOUND ABSORPTION USING A TWO-SCALE CHECKERBOARD META-SURFACE WITH MICRO HELMHOLTZ RESONATORS	3461
<i>Jeon Wonju, Ryoo Hyeonbin</i>	
REDUCING MECHANICAL CROSS-COUPLING IN PHASED ARRAY TRANSDUCERS USING ACOUSTIC METAMATERIAL AS BACKING	3464
<i>Henneberg Johannes, Gerlach André, Cebulla Holger, Marburg Steffen</i>	

ACOUSTIC MANIPULATION/LEVITATION

ACOUSTIC LEVITATION OF LARGE OBJECTS IN AIR	3468
<i>Andrade Marco A. B., Bernassau Anne, Okina Fábio T. A., Adamowski Julio C.</i>	
ACOUSTIC LEVITATION BY A METAMATERIAL-BASED ACOUSTIC CLOAK	3476
<i>Norasikin Mohd Adili, Memoli Gianluca, Martinez-Plasencia Diego, Subramanian Sriram</i>	
RECONFIGURABLE PARTICLE SEPARATION BY DYNAMIC ACOUSTIC FIELDS IN MICROFLUIDIC DEVICES	3484
<i>Simon Gergely, Roolvink Danny, Andrade Marco A. B., Reboud Julien, Marques-Hueso Jose, Desmulliez Marc P. Y., Burns Gerard, Cormack Peter A. G., Cooper Jonathan M., Riehle Mathis O., Bernassau Anne L.</i>	

MICRO-PERFORATED PANEL OR METAL FOAM ABSORBERS

SOUND BARRIERS FROM MICRO-PERFORATED PANEL ABSORBERS WITH SUB-CAVITIES AT DIFFERENT DEPTHS	3491
<i>Guo Wencheng, Min Hequn</i>	
NUMERICAL AND EXPERIMENTAL ANALYSES OF THE SOUND ABSORPTION OF PLAIN WEAVE FABRICS	3498
<i>Cai Zenong, Li Xianhui, Gai Xiaoling, Xing Tuo, Zhang Bin, Wang Fang</i>	
TRANSMISSION LOSS OF HELMHOLTZ WITH AN MICROPERFORATED PANEL INSERTION	3505
<i>Gai Xiaoling, Li Xianhui, Xing Tuo, Zhang Bin, Hu Wencheng, Cai Zenong, Wang Fang, Qin Qin</i>	
IMPACT CRUSHING BEHAVIORS OF FUNCTIONAL GRADED HONEYCOMB STRUCTURES WITH DEFECTS	3510
<i>Fan Tao</i>	

SUSTAINABLE ACOUSTIC MATERIALS

INVERSE ESTIMATION OF SOUND ABSORPTION COEFFICIENT OF NATURAL JUTE MATERIAL BASED ON PARTICLE SWARM OPTIMIZATION ALGORITHM	3517
<i>Mohanty Amiya, Bansod Pritesh</i>	
ACOUSTIC ABSORPTION OF GREEN WALLS MADE OF FOLIAGE AND SUBSTRATE LAYERS	3525
<i>Attal Emmanuel, Côté Nicolas, Shimizu Takafumi, Dubus Bertrand</i>	
CHICKEN FEATHER: AN ALTERNATIVE OF ACOUSTICAL MATERIALS	3531
<i>Kusno Asniawaty, Toyoda Masahiro, Sakagami Kimihiro, Okuzono Takeshi, Otsuru Toru, Kamil Kusno, Masgode Vovianty</i>	
STRAW AS AN ACOUSTIC MATERIAL	3539
<i>D'Alessandro Francesco, Schiavoni Samuele, Bianchi Francesco</i>	
INNOVATIVE AND SUSTAINABLE COATING SYSTEM: PRELIMINARY ACOUSTIC EVALUATION RESULTS	3547
<i>Scrosati Chiara, Scamoni Fabio, Piana Edoardo Alessio, Federici Maurizio, Zappella Sandra</i>	
NATURAL FIBRE COMPOSITES FOR ACOUSTIC APPLICATIONS	3555
<i>Lee Heow Pueh, Ang Linus Yinn Leng, Koh Yong Kiang, Tran Le Quan Ngoc</i>	

HUMAN RESPONSE TO NOISE AND VIBRATION

SOUND QUALITY EVALUATION USING HEART RATE VARIABILITY ANALYSIS	3560
<i>Ishimitsu Shunsuke, Oue Kento, Yamamoto Ayato, Date Yuki</i>	
EFFECTS OF SOUND INTERACTION AND VISUAL STIMULI ON SOUNDSCAPE QUALITY EVALUATION	3568
<i>Hao Yiyang, Kang Jian</i>	
THE CASE FOR AURAL DIVERSITY IN ACOUSTIC REGULATIONS AND PRACTICE: THE HAND DRYER NOISE PREDICAMENT	3576
<i>Drever John</i>	
USE OF A 3D PRINTED ARTIFICIAL EAR SIMULATION IN MEASURING HEARING RISK IN YOUNG PEOPLE	3582
<i>Davison Lee, Barlow Christopher</i>	

BIOACOUSTICS

FLUID-STRUCTURE INTERACTION ANALYSIS OF COCHLEA IN A FINITE ELEMENT MODEL WITH TRANSVERSE ISOTROPIC BASILAR MEMBRANE	3590
<i>Lee Dooho, Kang Seong-Jung</i>	
ON THE USE OF PARTIAL LEAST SQUARE REGRESSION FOR SPATIAL FITTING OF HEAD-RELATED TRANSFER FUNCTIONS	3596
<i>Wang Lei, Zeng Xiangyang, Yan Liang</i>	
AUTONOMOUS WILDLIFE SOUNDSCAPE RECORDING STATION USING RASPBERRY PI.....	3601
<i>Florentin Juliette, Verlinden Olivier</i>	
TERMITES THRIVE BY USING VIBRATIONS	3609
<i>Lai Joseph, Oberst Sebastian, Evans Theodore</i>	

PSYCHOACOUSTICS AND PRODUCT SOUND QUALITY

ARTIFICIAL NEURAL NETWORK BASED MODEL FOR THE CRISPNESS IMPRESSION OF THE POTATO CHIP SOUNDS.....	3617
<i>Altinsoy Ercan, Atamer Serkan</i>	
DEVELOPING FEELINGS OF EXCITEMENT FOR THE SOUND PRODUCED BY CAR ENGINES	3621
<i>Date Yuki, Ishimitsu Shunsuke, Yamamoto Ayato</i>	

SPEECH COMMUNICATION

FUNDAMENTAL RESEARCH OF SPEECH DISCRIMINATION FOR TONGUE THRUST USING ZERO-CROSSING AND MEL-FREQUENCY CEPSTRUM COEFFICIENTS	3626
<i>Nakayama Masashi, Ishimitsu Shunsuke, Yamashita Kimiko, Ishii Kaori, Kasai Kazutaka, Horiata Satoshi</i>	
EFFECTS OF AUDITORY FEEDBACK ON SINGING.....	3634
<i>Satoshi Iijima, Shunsuke Ishimitsu, Masashi Nakayama</i>	
AN ASSESSMENT OF OBJECTIVE INDICATORS OF SPEECH INTELLIGIBILITY IN NOISE AT LOW SIGNAL-TO-NOISE RATIOS	3642
<i>Graetzer Simone, Hopkins Carl</i>	
WEAKNESSES OF VOICE BIOMETRICS, SPEAKER VERIFICATION SPOOFING USING SPEECH SYNTHESIS	3650
<i>Rusko Milan, Darjaa Sakhia, Trnka Marian, Ritomský Marian</i>	

SUBJECTIVE ASSESSMENT OF BUILDING NOISE

SUBJECTIVE EVALUATION OF HEAVY/SOFT FLOOR IMPACT SOUND	3658
<i>Jeong Jeong-Ho, Kim Kyoung-Woo, Yang Kwan-Seop</i>	
RELATIONSHIP BETWEEN SUBJECTIVE RESPONSES AND PHYSICAL PARAMETERS FOR AIR-CONDITIONER NOISE	3663
<i>Soeta Yoshiharu</i>	
INFLUENCE OF NOISE SENSITIVITY ON PHYSIOLOGICAL RESPONSES TO FLOOR IMPACT SOUNDS	3671
<i>Park Sang Hee, Lee Pyoung Jik, Jeong Jeong Ho</i>	

ENVIRONMENTAL ROAD TRANSPORTATION NOISE

IMPROVING THE IN-SITU DETERMINATION OF THE INTRINSIC CHARACTERISTICS OF NOISE BARRIERS.....	3679
<i>Schwanen Wout, Hardeman Saskia, Wijnant Ysbrand</i>	
ACOUSTIC PERFORMANCE OF NOISE BARRIER DESIGNED FOR HIGH SPEED RAILWAY	3686
<i>Zhang Guoan, Lu Fan, Niu Junchuan, Sui Fusheng, Bai Guofeng</i>	
ENVIRONMENTAL ROAD TRANSPORTATION NOISE MONITORING: A NECESSARY TOOL FOR THE PROTECTION & REHABILITATION OF THE URBAN ACOUSTIC ENVIRONMENT.....	3693
<i>Vogiatzis Konstantinos, Kouroussis Georges</i>	

RAILWAY NOISE AND VIBRATION

HIGH SPEED RAILWAY NOISE PREDICTION FOR THE HS2 RAILWAY IN THE UNITED KINGDOM	3701
<i>Parry Graham, Yates David, Edwards Rebecca, Ledbetter Mike, Summers Steve</i>	
METHOD FOR CALCULATING THE PROBABILITY OF NOISE-INDUCED SLEEP STATE CHANGES FROM INTERMITTENT SOURCES OF TRANSPORTATION NOISE.....	3709
<i>Marshall Tom, Owen David, Greer Richard, Cobbing Colin, Sica Gennaro, Lowery Pamela</i>	
A STUDY ON SOUND RADIATIONS FROM A SLAB HIGH-SPEED RAILWAY TRACK SUBJECT TO A FAST-MOVING HARMONIC LOAD	3717
<i>Sheng Xiaozhen, Xiao Xinbiao</i>	

ABATEMENT OF RAIL NOISE IN GERMANY – MONITORING	3725
<i>Weinandy Rene, Appel Percy</i>	
ABATEMENT OF RAIL NOISE – ESPECIALLY FOR INFRASTRUCTURE	3731
<i>Appel Percy, Weinandy René</i>	
A HYBRID TWO-STEP APPROACH FOR EVALUATING THE IMPACT OF RAIL LOCAL DEFECT ON BUILDING VIBRATION	3738
<i>Kouroussis Georges, Vogiatzis Konstantinos, Connolly David</i>	
MODELLING OPTIONS FOR BALLASTED TRACK DYNAMICS	3746
<i>Shih Jou-Yi, Kostovasilis Dimitris, Bezin Yann, Thompson David</i>	
VIBRADYNA: A NEW VIBRATION PREDICTION MODEL	3754
<i>Burg Sander van der, Boon Pieter, Stuit Herke</i>	
INFLUENCES OF SURFACE ABRASIONS ON DYNAMIC BEHAVIOURS OF RAILWAY CONCRETE SLEEPERS	3758
<i>Kaewunruen Sakdirat, Ngamkhanong Chayut, Janeliukstis Rims, You Ruilin</i>	
ISOLATION OF VIBRATIONS INDUCED BY RAILWAY TRAFFIC IN DOUBLE-DECK TUNNELS USING ELASTOMERIC MATS	3766
<i>Clot Arnau, Arcos Robert, Noori Behshad, Romeu Jordi</i>	
AN INNOVATIVE NUMERICAL APPROACH FOR RAILWAY ROLLING NOISE FORECAST	3774
<i>Massimo Viscardi, Pasquale Napolitano, Maurizio Arena</i>	

VOLUME 6

RESEARCH OF NEW COMBINED TRACK SLAB SYSTEM IN LOW FREQUENCY VIBRATION CONTROL	3782
<i>Li Yuankang, Wang Anbin, Wang Zhiqiang, Li Qiang</i>	
THE INFLUENCE OF SENSORS MOUNTED CONDITION DURING GROUND BORNE VIBRATION MEASUREMENT	3790
<i>Wu Qiong, Zhang Lijuan, Hu Wencheng, Zhang Hougui</i>	
DISCUSS ON THE ACCEPTANCE CRITERIA FOR ACOUSTIC RAIL GRINDING	3796
<i>Zhang Hougui, Zhang Bin, Zhang Lijuan, Hecht Markus</i>	
ASYMETRICAL INFLUENCES ON NONLINEAR DYNAMICS OF RAILWAY TURNOUT Bearers	3804
<i>Kaewunruen Sakdirat, Minoura Shintaro, Papaalias Mayorkinos, Remennikov Alex</i>	
COMPUTATIONALLY EFFICIENT MODEL FOR CALCULATING THE 2.5D GREENS FUNCTIONS OF A TUNNEL BURIED IN A LAYERED HALF-SPACE SYSTEM	3811
<i>Noori Behshad, Arcos Robert, Clot Arnau, Romeu Jordi</i>	
ANALYSIS OF VERTICAL VIBRATION CHARACTERISTICS OF INFINITE PERIODIC SUPPORTED RAIL UNDER TEMPERATURE STRESS BY USING THE FOURIER TRANSFORM METHOD AND THE PERIODIC STRUCTURE THEORY	3818
<i>Feng Qingsong, Wang Wei, Liu Qingjie, Sheng Xiaozhen, Lei Xiaoyan</i>	

VEHICLE NOISE, VIBRATION AND HARSHNESS

THE NVH PACKAGE OF ELECTRIFIED PASSENGER VEHICLES: FUTURE CHALLENGES AND TRENDS	3825
<i>Ferrali Leonardo, Caprioli Davide, Cardillo Marco</i>	
RESEARCH ON THE ROAD TRAFFIC NOISE PREDICTION MODEL BASED ON IN SITE MEASUREMENT	3833
<i>Zhang Lijuan, Song Ruixiang, Yang Jie, Kang Zhongxu</i>	
DESIGN AND EVALUATION OF OPEN SPHERICAL MICROPHONE ARRAYS	3838
<i>Du Chaoran, Leclere Quentin, Li Baojiang</i>	
THE NONLINEAR GRNN MODEL OF MAGNETO-RHEOLOGICAL ENGINE MOUNTS AND FUZZY LOGIC CONTROL	3846
<i>Zheng Ling, Li Yinong, Deng Zhaoxue</i>	
BASIC RESEARCH ON HOT JUDDER OF CAR DISC BRAKES FROM THE VIEWPOINT OF SELF-EXCITED VIBRATION WITH TIME DELAY	3854
<i>Takahashi Kohei, Nakae Takashi, Ryu Takahiro</i>	
EFFECTS OF THE SYSTEM IMPERFECTIONS ON THE ISOLATION PERFORMANCE OF A QUASI-ZERO-STIFFNESS ISOLATOR	3862
<i>Meng Lingshuai, Ren Xudong, Sun Jinggong, Niu Fu, Xu Xinxu</i>	
TORSIONAL VIBRATION SUPPRESSION IN AUTOMATIC TRANSMISSION POWERTRAIN USING CENTRIFUGAL PENDULUM VIBRATION ABSORBER	3870
<i>Nakae Takashi, Ryu Takahiro, Matsuzaki Kenichiro</i>	
INVESTIGATION OF DYNAMIC CHARACTERISTICS FOR PEMFC MOUNTED ON VEHICLE	3878
<i>Ahn Sangkeun, Koh HyeongCheol, Park Junhong</i>	
DYNAMIC RESPONSE OF TWO-STATE HYDROMOUNTS WITH TWIN INERTIA TRACKS	3881
<i>Picken Judith, Thompson David, Daley Stephen</i>	
INFLUENCE OF TREAD DESIGN PARAMETERS ON AIR PUMPING NOISE IN AUTOMOTIVE TIRES	3889
<i>Oorath Rahul, Saraswat Abhishek, Gupta Shivashish Kumar, Tiwari Nachiketa, Goyal Sharad, Patel Chirag</i>	
SUPPORT VECTOR MACHINE CLASSIFIER FOR ENGINE MISFIRE DETECTION USING EXHAUST SOUND QUALITY	3897
<i>Singh Sneha, Potala Sagar, Mohanty Amiya</i>	

PERFORMANCE CHARACTERISTICS OF TWO AND THREE DOF QUARTER CAR MODELS WITH MAGNETORHEOLOGICAL DAMPER	3904
<i>Varala Rajath, I Sivakoteswarrao, Ashok Kumar Pandey</i>	
STRUCTURE DESIGN TO REDUCE WEIGHT AND VIBRATION BY USING STATISTICAL ENERGY ANALYSIS	3912
<i>Murayama Tomohide, Nakamura Hiroki, Nakamitsu Tsubasa, Kawabata Naoto, Yamazaki Toru</i>	
INVESTIGATION OF ATTENUATION MECHANISM OF NON-LINEAR DAMPER FOR SUPPRESSION OF MICRO-VIBRATION ON A CAR BODY	3920
<i>Nakamura Hiroki, Kamo Toshiaki, Ohsawa Hideki, Sakanoue Hiroshi, Yamazaki Toru</i>	

LRT AND HS RAIL NOISE AND VIBRATION MEASUREMENT AND CONTROL

THE COMPARISON ANALYSIS OF SOUND LEVEL EMITTED BY VARIOUS TRAM BOGIES UNDER NORMAL OPERATING CONDITIONS	3928
<i>Komorski Pawel, Nowakowski Tomasz, Szymanski Grzegorz M, Motyl Mateusz, Finke Szymon</i>	
ANALYSIS OF DYNAMIC TRAM-TRACK INTERACTIONS BASED ON PARASEISMIC VIBRATION	3936
<i>Nowakowski Tomasz, Tomaszewski Franciszek</i>	
AN INVESTIGATION INTO NOISE REDUCTIONS FOLLOWING A RAIL GRINDING CAMPAIGN ON DUBLIN'S LIGHT RAIL SYSTEM	3944
<i>Byrne Stephen</i>	
TRACKS WITH UNDER-BALLAST PLATES AND THEIR MITIGATION OF TRAIN INDUCED GROUND VIBRATION	3952
<i>Auersch Lutz</i>	
VIBRATION PREDICTION FOR HIGH SPEED TRAINS UTILISING THE PIPE IN PIPE MODEL TO DETERMINE GROUND BORNE NOISE LEVELS IN THE VICINITY OF DIFFERENT TUNNEL TYPES: MODEL VALIDATION	3960
<i>Summers Steve, Parry Graham, Ledbetter Mike, Edwards Rebecca, Mills Ben</i>	
THE INFLUENCE OF SLAB FOUNDATIONS ON GROUND-BORNE VIBRATION FROM RAILWAYS	3968
<i>Sanitate Giuseppe, Talbot James P</i>	
UNDERGROUND RAILWAY VIBRATION MEASUREMENT, ANALYSIS AND REDUCTION IN ADJACENT RESIDENTIAL BUILDINGS	3976
<i>Tsukernikov Ilya, Smirnov Vladimir, Shubin Igor, Nevenchannaya Tatiana</i>	

GROUND BORNE NOISE AND VIBRATION

NUMERICAL MODELLING OF THE GROUND-BORNE VIBRATIONS GENERATED BY TRUCK-ROAD INTERACTION	3984
<i>Kouroussis Georges, Ducarne Loic, Ainalis Daniel</i>	
THE IMPORTANCE OF INCLUDING BEARING STIFFNESS IN STRUCTURAL ANALYSIS	3992
<i>Kelly Roger</i>	
AN AUDIO DEMONSTRATION OF HOW ARE EARS ARE MORE SENSITIVE TO CHANGES IN LOW FREQUENCY NOISE – FOR INSTANCE GROUND-BORNE NOISE FROM TUBE TRAINS	3997
<i>Kelly Roger</i>	
FORMULATING HYBRID MODELS FOR PREDICTION OF RAILWAY INDUCED VIBRATION LEVELS IN BUILDINGS	4000
<i>Kuo Kirsty, Lombaert Geert, Degrande Geert</i>	
PREDICTING GROUND BORNE NOISE FROM VIBRATION OF RADIATING BUILDING ELEMENTS USING POWER BASED BUILDING ACOUSTICS THEORY	4008
<i>Villot Michel, Jean Philippe, Grau Loic</i>	
DYNAMIC STIFFNESS AND DESIGN OF RUBBER-STEEL LAMINATED ISOLATORS	4016
<i>Picken Judith, Muhr Alan, Ahmadi Hamid</i>	
A NEW EMPIRICAL PREDICTION APPROACH FOR GROUND BORNE VIBRATION IN BUILDINGS	4021
<i>Lurcock Daniel, Thompson David</i>	
NOISE AND VIBRATION PROBLEM IN THE NEIGHBORHOOD OF THE BUDAPEST M4 METRO LINE	4029
<i>Nagy Daniel Szilveszter, Bite Maria, Varfi Laszlo</i>	

TYRE ROAD INTERACTIONS AND LOW NOISE PAVEMENTS

PARAMETER IDENTIFICATION OF AGRICULTURAL TIRE BY USING RIGID RING MODEL	4037
<i>Fujita Katsuhide, Saito Takashi, Kaneko Mitsugu</i>	
A GUIDELINE FOR SUSTAINABLE LOW NOISE PAVEMENTS	4045
<i>Hammer Emanuel, Bühlmann Erik</i>	
HOW WELL CAN THE CLOSE-PROXIMITY (CPX) METHOD REPLACE THE STATISTICAL PASS-BY (SPB) METHOD IN THE EVALUATION OF THE NOISE REDUCING PERFORMANCE OF PAVEMENTS	4053
<i>Van Loon Ronald</i>	

ESTIMATING THE RESISTIVITY AND TORTUOSITY OF A ROAD PAVEMENT USING AN INVERSE PROBLEM APPROACH	4061
<i>Praticò Filippo Giammaria, Vizzari Domenico, Fedele Rosario</i>	

ACOUSTICS AND SUSTAINABILITY IN SCHOOLS

CLASSROOM ACOUSTICS OF MCNEESE STATE UNIVERSITY.....	4069
<i>Chaudhary Aash, Li Zhuang</i>	
ACOUSTIC CONDITIONS FOR SPEECH COMMUNICATION IN ELEMENTAL SCHOOL CLASSROOMS	4077
<i>Jianxin Peng</i>	

EVALUATION OF ACOUSTICAL QUALITY OF SPACES INCLUDING HERITAGE BUILDINGS

ACOUSTIC EVALUATION OF THE CATHEDRALS OF MURCIA AND TOLEDO, SPAIN.....	4083
<i>Girón Sara, Álvarez-Morales Lidia, Galindo Miguel, Zamarreño Teófilo</i>	
ACOUSTICAL PERFORMANCE OF MOSQUES: AN OVERVIEW OF CURRENT RESEARCH IN MALAYSIA	4091
<i>Nazli Che Din, Zufar Adzahan, Mokhtar Harun, Mohamad Ngasri Dimon, Zunaibi Abdullah</i>	
ACOUSTICAL STUDIES OF WORSHIP SPACES IN HINDU TEMPLES	4098
<i>Prasad M.G., Rajavel B.</i>	
DESIGN CONSIDERATIONS FOR IMPROVEMENT OF SPEECH INTELLIGIBILITY AND PRIVACY IN A HOSPITAL INTENSIVE CARE UNIT.....	4106
<i>Utami Sentagi Sesotya, Sarwono Joko, Yanti Ressay Jaya, Fela Randy Frans, Azzahra Iva Rofiatun Nisa</i>	
IMPACT THAT ACOUSTIC DESIGN HAS ON HIGHER EDUCATION FOR NON-ENGLISH SPEAKING STUDENTS.....	4114
<i>Sanchez-Pizani Rodrigo, Dance Stephen</i>	
ASSESSMENT OF LOW FREQUENCY QUALITY METRICS IN SMALL ROOMS.....	4122
<i>Palma Jorge Ignacio Calderon De, Masson Florent</i>	
A 3D SOUND PARTICLE MODEL WITH UNCERTAINTY-BASED DIFFRACTION FOR GENERAL GEOMETRIES.....	4130
<i>Judd Thomas, Schaal Jochen</i>	

ACOUSTICAL DESIGN OF HALLS: EXAMPLES AND SUGGESTIONS

THE ACOUSTIC DESIGN OF OPERA HOUSE DUBAI	4136
<i>Howarth Mark, Robinson Matt</i>	

LEO BERANEK MEMORIAL SESSION – A CENTURY OF ROOM ACOUSTICS

LEO BERANEK - A LIFE IN ACOUSTICS 1914 - 2016.....	4144
<i>Barron Mike</i>	
OPTIMIZING VARIABLE ACOUSTIC SURFACES.....	4153
<i>Moller Henrik</i>	
CREATIVE POSSIBILITIES AND LIMITATIONS OF CURVED SURFACES IN THE ACOUSTIC DESIGN OF CONTEMPORARY AUDITORIA.....	4161
<i>Wulfrank Thomas, Kahle Eckhard, Green Evan, Gomez Juan Oscar Garcia</i>	
ANALYSIS OF MUSIC PERFORMED IN DIFFERENT ACOUSTIC SETTINGS IN STAVANGER CONCERT HALL.....	4169
<i>Halmrast Tor</i>	
ACOUSTICS IN BETWEEN: PERCEPTION OF SOUND IN ROOMS BEYOND STANDARD CRITERIA.....	4177
<i>Halmrast Tor</i>	
BEYOND SABINE: INVESTIGATING THE ACOUSTICAL PHENOMENON OF REVERBERATION USING ROOM MODAL DECAY.....	4185
<i>Economou Panos, Economou Costas, Charalampous Panagiotis</i>	
CONCERT HALL ACOUSTICS, ONLINE RATING AND BERANEKS DATA COLLECTION	4193
<i>Skalevik Magne</i>	
SPATIAL LISTENING ASPECTS AND THE TIME-VARYING INTER-AURAL CROSS-CORRELATION DURING MUSIC PERFORMANCE IN CONCERT HALLS	4201
<i>Skalevik Magne</i>	
CHARACTERISTICS OF SOUND PRESSURE LEVEL IN EXTRA-LARGE SPACES.....	4209
<i>Wang Chao, Ma Hui, Kang Jian</i>	

PSYCHOACOUSTICAL ASPECTS OF SPATIAL ACOUSTICS

DESIGN AND IMPLEMENTATION OF AN AUDIOVISUAL TRACK WITH THE SUPPORT OF AMBIOPHONICS SYSTEM - PART I: PRELIMINARIES.....	4215
<i>Arrieta Laura Nataly Villa, Leon Natalia del Pilar Farfan, Martínez Marcelo Herrera</i>	

CREATING A PSYCHOLOGICALLY SUPPORTIVE ENVIRONMENT THROUGH AURAL ARCHITECTURE	4223
<i>Algargoosh Alaa</i>	

SURFACE MATERIALS: HANDLING ABSORPTION/DIFFUSION PROPERTIES

INPUT DATA FOR ACOUSTICAL DESIGN CALCULATIONS FOR ORDINARY PUBLIC ROOMS.....	4231
<i>Nilsson Erling</i>	
ROOM ACOUSTICS DIFFUSERS: PYRAMIDS AND WEDGES	4239
<i>Cox Trevor</i>	
ESTIMATING THE SABINE ABSORPTION COEFFICIENT OF FIBROUS MATERIALS FOR VARIOUS BACKING CONDITIONS	4247
<i>Jeong Cheol-Ho</i>	
A SYNTHESIZED BOUNDARY CONDITION USING ENSEMBLE AVERAGED SURFACE NORMAL IMPEDANCE FOR WAVE-BASED ROOM ACOUSTICS SIMULATIONS	4253
<i>Otsuru Toru, Tomiku Reiji, Okamoto Noriko, Yamauchi Saki, Saigo Sakura</i>	

PERCEPTION OF AURALISED SPACE

SUBJECTIVE ASSESSMENT OF AURALIZATIONS CREATED BY MEANS OF GEOMETRICAL ACOUSTICS AND FINITE ELEMENT NUMERICAL METHODS	4260
<i>Jimenez Luis Alberto Tafur, Sanchez Santiago Ruiz, Villegas Jonathan Ochoa, Ciro Libardo Antonio Londono</i>	
APPLICATION OF AURALIZATIONS TO EVALUATE THE INFLUENCE OF REVERBERATION AND BACKGROUND NOISE ON INTELLIGIBILITY AND LISTENING DIFFICULTY OF A CLASSROOM	4268
<i>Tafur Luis Alberto, Ochoa Jonathan, Ruiz Santiago</i>	
PROPOSAL OF AN INTERACTIVE AUDIO INSTALLATION MODULE FOR THE COLOMBIAN NATIONAL PARK	4276
<i>Muñoz Diana Carolina Martinez, Bustos Shimmy Garcia, Martínez Marcelo Herrera, Betancourt Manuel Alejandro Mayorga</i>	
DESIGN AND IMPLEMENTATION OF AN AMBISONICS SYSTEM CODEC	4284
<i>López Andrés Felipe Espitia, Cruz Diego Federico Barco, Martínez Marcelo Herrera</i>	

ACOUSTICS IN OPEN PLAN OFFICES

IRRELEVANT SPEECH EFFECT IN OPEN PLAN OFFICES : A LABORATORY STUDY	4292
<i>Kostallari Krist, Parizet Etienne, Chevret Patrick, Amato Jean-Noël, Galy Edith</i>	
CONTRASTING OPEN PLAN OFFICE DESIGN IMPLICATIONS FROM EMERGING FRENCH, GERMAN AND FINNISH STANDARDS	4300
<i>Harvie-Clark Jack, Larrieu Felix</i>	
PROPOSED METHOD FOR MEASURING LIVELINESS IN OPEN PLAN OFFICES	4308
<i>Vellenga Sara, Hongens Theodoor, Bouwhuis Tom</i>	
TROUBLE SHOOTING IN AN OPEN PLAN OFFICE: CASE STUDY	4316
<i>Asselineau Marc, Gaulupeau Aline</i>	
PRACTICAL CONSIDERATIONS AND EXPERIENCES WITH SOUND MASKING'S LATEST TECHNOLOGY	4320
<i>Edgington Charles, Stevens Mark</i>	
AUDIO-VISUAL PREFERENCES OF WATER FEATURES USED IN OPEN-PLAN OFFICES	4324
<i>Abdalrahman Zanyar, Galbrun Laurent</i>	
SUBJECTIVE RATING AND OBJECTIVE EVALUATION OF THE ACOUSTIC AND INDOOR CLIMATE CONDITIONS IN VIDEO CONFERENCING ROOMS.	4332
<i>Hauervig-Jørgensen Charlotte, Jeong Cheol-Ho, Toftum Jørn, Christensen Emine Celik</i>	

HEALTHCARE ACOUSTICS

A REVIEW OF THE EFFECTIVENESS, PRACTICAL IMPLICATIONS AND IMPACT OF GUIDELINES ON ACOUSTIC CONDITIONS IN UK HEALTHCARE PREMISES	4339
<i>Budd Richard</i>	
ASSOCIATIONS OF ACOUSTIC ENVIRONMENT WITH PHYSIOLOGICAL AND PSYCHOLOGICAL STATES AMONG HOSPITALIZED PATIENTS IN GENERAL HOSPITAL WARDS	4346
<i>Deng Zhixiao, Xie Hui, Kang Jian</i>	
NOISE LEVELS AND NOISE SOURCES IN THE OPERATING THEATRES	4353
<i>Liu Weifan, Xie Hui</i>	
ANXIETY IN MURINE CAUSED BY COMBINED AND SINGLE TRAFFIC NOISES: A CONTRASTIVE STUDY	4361
<i>Guoqing Di, Yaqian Xu</i>	

MODAL AND FINITE ANALYSIS FOR ACOUSTICS AND VIBRATION

EFFICIENT SIMULATION OF LARGE STRUCTURAL-ACOUSTIC SYSTEMS USING COMPONENT MODE SYNTHESIS METHOD	4369
<i>Mi Yongzhen, Zheng Hui</i>	
MEASURING MODAL DAMPING OF A MULTIBODY SYSTEM WITH DRY FRICTION	4375
<i>Magyar Balint, Zana Roland, Wohlfart Richard, Csernak Gabor, Stepan Gabor</i>	
CLUSTERIZATION FOR DERIVING EIGENPAIRS OF A VIBRO-ACOUSTIC RECTANGULAR CAVITY	4382
<i>Tanaka Nobuo, Iwamoto Hiroyuki</i>	
EXPERIMENTALLY VERIFIED NUMERICAL TECHNIQUE FOR GAS-TURBINE BLADES DAMPING MODELLING BASED ON SUBSTRUCTURE METHOD	4390
<i>Sazhenkov Nikolai, Semenova Irina, Nikhamkin Mikhail, Semenov Sergei</i>	
THE EFFECT OF VIBRATION LOCALIZATION ON THE PERFORMANCE OF A VISCOUS DAMPER	4398
<i>Mori Hiroki, Nagamine Takuo, Sato Yuichi</i>	
A NOVEL METHOD FOR DYNAMIC CHARACTERIZATION OF POLYMERIC VIBRATION DAMPERS	4405
<i>Barbieri Marco, De Felice Alessandro, Pellicano Francesco, Sorrentino Silvio, Zippo Antonio</i>	
MODAL LOCALIZATION IN VIBRATING CIRCULAR CYLINDRICAL SHELLS	4412
<i>Pellicano Francesco, Zippo Antonio, Strozzi Matteo, Barbieri Marco</i>	
OPTIMIZATION OF PLANETARY GEAR SYSTEMS BY MEANS OF GENETIC ALGORITHM	4420
<i>Masoumi Asma, Barbieri Marco, Pellicano Francesco</i>	
A SIMULATION BASED STUDY OF LOW FREQUENCY TRANSIENT SOUND RADIATION FROM FLOORS – A CONCRETE VS. A HYBRID FLOOR	4428
<i>Linderholt Andreas, Olsson Jörgen</i>	
VIBRATION OF FUNCTIONALLY GRADED CYLINDRICAL SHELLS	4436
<i>Zippo Antonio, Pellicano Francesco, Barbieri Marco, Strozzi Matteo</i>	
A METHODOLOGY FOR VIRTUAL SOUND SYNTHESIS FOR GRAPHICAL OBJECT INTERACTIONS	4444
<i>Park Sang Un, Imran Muhammad, Jeon Jin Yong</i>	
OPTIMISATION OF A THREE MASS-THREE SPRING VIBRATION ENERGY HARVESTING SYSTEM.	4448
<i>Bridge Jacqueline</i>	
RESEARCH ON ENDOVASCULAR STENTS' BASIC MECHANICAL PROPERTIES AND COUPLED VIBRATION WITH VASCULAR WALL	4456
<i>Li Ke, Li Hong</i>	

ROTOR DYNAMICS SIMULATION FOR ACOUSTICS AND VIBRATION

IDENTIFICATION OF FOUNDATIONS IN ROTATING MACHINERY WITH NON-PROPORTIONAL HYSTERETIC DAMPING ASSUMPTION	4464
<i>Yu Minli, Feng Ningsheng, Hahn Eric, Liu Jike</i>	
VALIDATION OF THE VIBRATIONAL BEHAVIOUR OF ELECTRICAL MACHINES UNDER ELECTROMAGNETIC EXCITATION USING MANATEE SOFTWARE AND ALTAIR OPTISTRUCT	4472
<i>Regniet Margaux, Bonneel Pierre, Le Besnerais Jean</i>	
NONAXISYMMETRICAL VIBRATION MODES OF ROTOR SYSTEM SIMULATION USING EXPERIMENTALLY VERIFIED SUPERELEMENTS	4480
<i>Semenov Sergey, Semenova Irina, Nikhamkin Mikhail, Sazhenkov Nikolai, Mekhonoshin Grigori</i>	
A SUBSYSTEM-BASED ANALYTICAL METHOD ON CHARACTERIZING THE VIBRO-ACOUSTICS OF HIGH-SPEED BRUSHLESS MOTORS	4488
<i>Ji Lin, Faventi Roberto, Lamb John, Kowalczyk Lukasz</i>	
INSIGHTS INTO THE GYROSCOPIC BEHAVIOUR OF AXIALLY AND TORSIONALLY LOADED ROTATING SHAFTS	4496
<i>De Felice Alessandro, Sorrentino Silvio</i>	
1D MODELLING OF ENGINE CRANKSHAFT: IMPACT OF IGNITION TIMING ON CRANKSHAFT TORSIONAL VIBRATIONS	4504
<i>Bianciardi Fabio, Janssens Karl, Britte Laurent</i>	

PATTERN RECOGNITION FOR ACOUSTICS AND VIBRATION

FEATURE EXTRACTION AND RECOGNITION OF WALL IMPACT NOISES	4511
<i>Zeng Xiangyang, Wang Qiang, Wang Lu, Lu Chenxiang</i>	
UNDERWATER ACOUSTIC SIGNAL CLUSTERING WITH PROBABILISTIC LINEAR DISCRIMINANT ANALYSIS AND DIRICHLET PROCESS	4516
<i>Wang Qiang, Zeng Xiangyang, Wang Lu</i>	
COMPENSATING ACOUSTIC MISMATCH FOR ROBUST SPEAKER VERIFICATION	4524
<i>Ramirez Víctor Poblete, Paulsen Isaac González, Montenegro Alexandra Astudillo, Díaz Gaston Vergara</i>	
DAMAGE DETECTION INTO ROAD PAVEMENTS THROUGH ACOUSTIC SIGNATURE ANALYSIS: FIRST RESULTS	4532
<i>Fedele Rosario, Praticò Filippo Giammaria, Carotenuto Riccardo, Corte Francesco Giuseppe Della</i>	

VOLUME 7

NOISE ROBUST FEATURE EXTRACTION FOR UNDERWATER TARGETS CLASSIFICATION VIA LABEL CONSISTENT DICTIONARY LEARNING	4540
<i>Wang Lu, Chen Lin, Zeng Xiangyang</i>	

NUMERICAL METHODS AND SIMULATION FOR ACOUSTICS AND VIBRATION

DEVELOPING INHERENT CHARACTERISTICS OF REACTIVE PRESSURE PULSATION DAMPER	4546
<i>Mironova Tatiana, Prokofiev Andrey</i>	
AN IMPROVED MULTI-HARMONIC BALANCE METHOD FOR NONLINEAR DYNAMIC ANALYSIS OF JOINT INTERFACE	4553
<i>Wang Dong, Feng Jiaquan, Hu Jie, Wan Qiang</i>	
A NEW CABLE ELEMENT USING THE ABSOLUTE NODAL COORDINATE FORMULATION.....	4561
<i>Xin Pengfei, Rong Jili, Zhuge Xun</i>	
VIBRATION ANALYSIS OF CURVED FRAMES.....	4565
<i>Syam B. K., Sarkar Abhijit, Priyadarshan P.</i>	
A HYBRID HIGH-ORDER SLIDING MESH INTERFACE FOR FINITE DIFFERENCE SCHEMES	4573
<i>Fattah Ryu, Zhang Xin</i>	
ANALYSIS OF THE DYNAMICS OF THE FLYWHEEL WITH NONLINEAR VIBRATION ABSORBER USING THE WAVELETS	4581
<i>Liu Haiping, Wang Yaobing, Sun Pengfei, Xu Zhe</i>	
AN ITERATIVE SPECTRAL METHOD FOR COMPUTING STATIONARY DYNAMIC RESPONSES OF PLANETARY GEARS PARAMETRICALLY EXCITED BY THE MESHING STIFFNESSES.....	4589
<i>Perret-Liaudet Joel, Neufond Jessica, Xu Yuiyang, Rigaud Emmanuel</i>	
FREE VIBRATION ANALYSIS OF A CLASSICAL H-SHAPED FRAME BY A THREE-DIMENSIONAL STRUCTURAL MODEL	4593
<i>Mei Carole</i>	
A NOVEL SPECTRAL DYNAMIC STIFFNESS METHOD FOR EFFICIENT AND EXACT ELASTODYNAMIC ANALYSIS WITHIN THE WHOLE FREQUENCY RANGE	4600
<i>Liu Xiang, Banerjee J. Ranjan</i>	
ON THE CHOICE OF CONDENSATION FUNCTIONS FOR MID-TO-HIGH FREQUENCY VIBROACOUSTIC MODELLING	4608
<i>Hu Zhongyu, Maxit Laurent, Cheng Li</i>	
ANALYSIS OF GEAR DYNAMICS OF A HELICAL GEAR PAIR WITH FAULTS	4616
<i>Huang Yi-Mei, Huang Kai-Yu</i>	
SYSTEM-LEVEL MULTI-BODY SIMULATIONS OF A WIND TURBINE GEARBOX	4624
<i>Shweiki Shadi, Mundo Domenico, Palermo Antonio, Francesco Gagliardi</i>	
THIRD-ORDER ACOUSTIC FINITE ELEMENTS AND H-ADAPTIVITY FOR EFFICIENT ACOUSTIC SIMULATIONS.....	4632
<i>Cordaro Thomas, Talbot Alexis, Lielens Gregory</i>	
THE RELIABILITY ANALYSIS OF STOCHASTIC NONLINEAR VIBRATION SYSTEM WITH FAILURE INTERACTION	4640
<i>Lu Hao, Tang Chaoquan, Zhang Yimin</i>	
ON BRYAN'S LAW AND ANISOTROPIC NONLINEAR DAMPING	4645
<i>Joubert Stephan V, Shatalov Michael Y, Fay Temple H, Sedebo Getachew T</i>	
NONLINEAR FREE VIBRATION OF SHEAR DEFORMABLE FUNCTIONALLY GRADED POROUS BEAMS	4653
<i>Yang Jie, Chen Da, Kitipornchai Sritawat</i>	
SIMULTANEOUS EXCITATIONS-INDUCED WIDEBAND FREQUENCY RESPONSE IN NONLINEAR COUPLED PERIODIC PENDULUMS	4661
<i>Jallouli Aymen, Kacem Najib, Bouhaddi Nouredine</i>	
HIGH ORDER ANSATZ FUNCTIONS ON ISOGEOMETRIC BOUNDARY ELEMENTS	4669
<i>Keuchel Sören, Hagelstein Nils Christian, Zaleski Olgierd, von Estorff Otto</i>	
A MODE SHAPE BASED APPROXIMATION FOR PARAMETER-DEPENDENT EIGENVALUE PROBLEMS ARISING IN STRUCTURAL VIBRATION	4676
<i>Gavryliuk Nataliia, Bhaskar Atul</i>	
SOUND INSULATION OF HOMOGENEOUS SINGLE PANELS: A COMPARISON BETWEEN REAL CONSTRUCTION MATERIALS AND SEVERAL PREDICTION MODELS.....	4684
<i>Mansilla Joaquin, Masson Florent, Palma Ignacio Calderon de, Pepino Leonardo, Bender Laurence</i>	
ANALYSIS OF FREQUENCY LOCI VEERING PHENOMENA IN DETUNED SPHERICAL RETICULATED SHELL	4692
<i>Liu Zhanhui, Zhang Ming, Zhang Keyue, Liu Wei, Gao Weicheng</i>	
NUMERICAL STUDY ON NONLINEAR VIBRATIONS, ENERGY EXCHANGE AND RESONANT INTERACTIONS IN SINGLE WALLED CARBON NANOTUBES	4700
<i>Strozzi Matteo, Barbieri Marco, Zippo Antonio, Pellicano Francesco</i>	
INTRINSIC LOCALIZED MODES IN PERIODIC NONLINEAR LATTICES UNDER SIMULTANEOUS EXCITATIONS	4708
<i>Bitar Diala, Kacem Najib, Bouhaddi Nouredine</i>	

FLOW INDUCED VIBRATIONS OF A RECTANGULAR DUCT: ACOUSTIC AND TURBULENT EXCITATIONS	4716
<i>Hugues Florian, Perrey-Debain Emmanuel, Dauchez Nicolas</i>	
FRF-BASED PROBABILISTIC MODEL UPDATING IN STRUCTURAL DYNAMICS FOR UNCERTAINTY IDENTIFICATION AND QUANTIFICATION.....	4722
<i>Arora Vikas, Adhikari S., Friswell M.I.</i>	
NUMERICAL CODE FOR DESCRIBING ACOUSTIC WAVE PROPAGATION IN SOLIDS CONTAINING CRACKS OF KNOWN GEOMETRY.....	4730
<i>Delrue Steven, Aleshin Vladislav</i>	
DYNAMIC LOAD IDENTIFICATION ON NONLINEAR DAMPING STRUCTURE USING POSITIVE DEDUCTION APPROACH.....	4738
<i>Lei Xiaofei, Wu Chengjun</i>	
WAVENUMBER-FREQUENCY SPECTRUM OF TURBULENT FLUCTUATING PRESSURE ON AIRFOIL SURFACE	4746
<i>Wu Hong-Liang, Zhou Qi-Dou, Pan Yu-Cun</i>	
THE STATISTICAL PROPERTIES OF RANDOM FREQUENCY RESPONSE FUNCTIONS.....	4754
<i>Langley Robin</i>	
PREDICTION OF VIBRATION TRANSMISSION ACROSS PLATE JUNCTIONS WITH A PERIODIC RIBBED PLATE US-ING SEA AND ASEA.....	4762
<i>Yin Jianfei, Hopkins Carl, Yang Haibin</i>	
VIBRATION OF AN EXPONENTIALLY TAPERED ROD EMBEDDED IN AN ELASTIC SOLID - A PIECEWISE UNIFORM APPROACH.....	4770
<i>Kalkowski Michal, Muggleton Jen Muggleton, Rustighi Emiliano</i>	
HARMONIC BALANCE COMPUTATION OF THE NONLINEAR FREQUENCY RESPONSE OF A THIN PLATE	4778
<i>Lee Jongsuh, Detroux Thibaut, Kerschen Gaëtan</i>	
 <u>NUMERICAL SIMULATION IN VEHICLE ACOUSTICS</u>	
USING EXPERIMENTAL STATISTICAL ENERGY ANALYSIS TO DETERMINE LOSS FACTORS FOR COUPLED SPACE SUBSYSTEMS IN A CAR CABIN	4784
<i>Jang Hyoseon, Hopkins Carl</i>	
NOISE PREDICTION AND REDUCTION ON INTERIOR ACOUSTIC FIELD OF LAUNCH VEHICLE FAIRINGS.....	4791
<i>Cheng Xiuyan, Rong Jili, Chen Xiangyu</i>	
A HYBRID FEM-SEA APPROACH FOR THE VIBRO-ACOUSTIC ANALYSIS OF VEGA-C LAUNCHER AT LIFT OFF.....	4796
<i>Vitiello Pasquale, Citarella Roberto, D'Andria Enrico, Federico Luigi</i>	
NUMERICAL ANALYSIS OF THE ACOUSTIC PERFORMANCE OF TREATMENTS USED FOR ENGINE ENCAPSULATIONS	4804
<i>Vansant Koen, Bertolini Claudio, Miccoli Giuseppe</i>	
NUMERICAL SIMULATION AND EXPERIMENTAL VALIDATION OF NORMAL STRAIN DISTRIBUTION AND PITTING PHENOMENON IN INDUSTRIAL GEARS	4812
<i>Strozzi Matteo, Barbieri Marco, Zippo Antonio, Pellicano Francesco</i>	
NUMERICAL STUDY OF TRANSFER FUNCTION OF COMBUSTION NOISE ON A HEAVY DUTY DIESEL ENGINE	4820
<i>Ciylez Ibrahim, Erol Haluk</i>	
 <u>ADVANCED SIGNAL PROCESSING ON SOUND AND VIBRATION</u>	
DEVELOPMENT OF AN ADAPTIVE NOISE REDUCTION SYSTEM WITH AUTOMATIC WIND NOISE DETECTION UTILIZING TMS320C6713.....	4828
<i>Wu Chao-Min, Luo Wei-lun, Liu Ting-An</i>	
IMPROVED GENERALIZED CROSS-CORRELATION ALGORITHM FOR TIME DELAY ESTIMATION BASED ON SECONDARY CORRELATION AND DATA SEGMENTATION	4836
<i>Yu Wenjing, He Lin</i>	
VALIDATION OF A WAVELET DECONVOLUTION METHOD FOR EXPERIMENTAL DETERMINATION OF THE FORCE APPLIED BY LIQUID WATER DROPS.....	4844
<i>Yu Yicheng, Hopkins Carl</i>	
FAULT CLASSIFICATION OF DIFFERENTIAL GEARBOX BASE ON MULTI CLASS SVM FROM TIME-FREQUENCY VIBRATION DATA	4852
<i>Ebrahimi Ebrahim</i>	
INDOOR SOUND SOURCE LOCALIZATION USING A ROOM FEATURE-BASED METHOD.....	4858
<i>Wang Haitao, Zeng Xiangyang, Wang Lu, Liu Yanshan</i>	
OPTIMIZING BEAMPATTERNS FOR A CONFORMAL ARRAY MOUNTED ON AN AXISYMMETRIC BODY IN FLOW NOISE FIELD.....	4866
<i>Li Xuegang, Chen Ming, Sun Guocang, Lei Chengyou, Li Honggang</i>	

APPLICATION OF HIGHER ORDER SPECTRA FOR THE FATIGUE LOAD CHARACTERISATION OF NON-GAUSSIAN RANDOM VIBRATION SIGNALS	4874
<i>Hammer Arthur, Wolfsteiner Peter</i>	
A SERIES OF VARIABLE STEP-SIZE FXLMS ALGORITHMS FOR NARROWBAND ACTIVE NOISE CONTROL	4882
<i>Yegui Xiao, Haofei Zhang, Jian Liu</i>	
VEHICLE LOCALIZATION AND TRACKING USING ACOUSTIC SENSORS BASED ON TIME DIFFERENCE OF ARRIVAL METHOD	4889
<i>Kai Zhang, Diange Yang, Feng Miao, Xiaomin Lian</i>	
HEAD-TRACKED AURALISATIONS FOR A DYNAMIC AUDIO EXPERIENCE IN VIRTUAL REALITY SCENERIES.....	4897
<i>Ballesterio Eric, Robinson Philip, Dance Stephen</i>	
DEFINITION OF STATIONARITY BASED ON MONITORING THE UNCERTAINTY AT REAL MEASUREMENT CONDITIONS	4905
<i>Heiss Alois</i>	
AN ULTRASONIC WIRELESS DATA FEEDTHROUGH SYSTEM BASED ON FIELD PROGRAMMABLE GATE ARRAY	4913
<i>Yang Hengxu, Zhang Jianing, Yu Ziyang, Wu Ming, Yang Jun</i>	
AMPLITUDE DEPENDENCE OF MODAL PROPERTIES IN LATERAL VIBRATION OF TIMBER BUILDINGS.....	4921
<i>Reynolds Thomas</i>	
NON-LINEAR BROADBAND BEAMFORMER WITH DEEP NEURAL NETWORK	4929
<i>Mizumachi Mitsunori, Origuchi Maya, Nishijima Yuya</i>	
FAULT DIAGNOSIS OF ROLLING BEAR USING GENERALIZED ORTHOGONAL MATCHING PURSUIT.....	4935
<i>Xu Juan, Huang Jingkun, Shi Lei, Zhang jianjun</i>	
AN ATTEMPT OF DISTANCE MEASUREMENT FOR A HUMAN BASED ON PHASE INTERFERENCE USING BEAM-STEERING AT EACH CHANNEL OF PARAMETRIC ARRAY LOUDSPEAKER	4943
<i>Nakasako Noboru, Nakano Tomofumi, Shinohara Toshihiro, Nakayama Masato, Uebo Tetsuji</i>	
COMPARISON OF ADAPTIVE AND DIRECTIONAL OPTIMAL SENSOR WEIGHTS IN ISOTROPIC NOISE FIELDS.....	4951
<i>Cray Benjamin, Kirsteins Ivars</i>	
 <u>NUMERICAL METHODS IN UNDERWATER ACOUSTICS</u>	
ANALYSIS OF THE MULTIPLE CYLINDRICAL SHELL-PLATE COUPLED SYSTEM VIBRATION CHARACTERISTIC WITH ELASTIC BOUNDARY	4954
<i>Cao Yipeng, Wang Jinzhao, Lin Guang</i>	
ASSESSMENT OF PERMEABLE BOUNDARY INTEGRAL FORMULATIONS FOR ROTATING BLADES NOISE PREDICTION	4962
<i>Porcacchia Federico, Testa Claudio, Zaghi Stefano, Muscari Roberto, Gennaretti Massimo</i>	
THE EFFECT OF FLOATING DECK STRUCTURES ON UNDERWATER RADIATED NOISE	4970
<i>Boschaart Casper, Jansen Erwin, Jong Christ de, Basten Tom</i>	
NUMERICAL APPROACHES IN GEOACOUSTIC INVERSION	4978
<i>Dosso Stan E., Dong Hefeng, Duffaut Kenneth</i>	
 <u>RADIATION, ABSORBING AND SCATting FROM UNDERWATER OBJECTS</u>	
PREDICTED DETECTION OF AN EMERGENCY UNDERWATER LOCATOR BEACON.....	4986
<i>Brown Adrian</i>	
 <u>UNDERWATER NOISE MEASUREMENT AND MONITORING</u>	
UNDERWATER NOISE LIMITS AND MEASUREMENT OF UNDERWATER RADIATED NOISE FROM MERCHANT VESSELS.....	4994
<i>Lorenzo Francesco De, Oliva Adrià, White Paul R.</i>	
A COMPARISON OF METHODS FOR MEASURING SHIP SOURCE LEVEL IN SHALLOW WATER.....	5002
<i>Wang Lian, Robinson Stephen</i>	
MEASUREMENT OF THE UNDERWATER NOISE FOOTPRINT OF A VESSEL.....	5007
<i>Humphrey Victor, Brooker Alex</i>	
ACOUSTIC MEASUREMENT AND MODELLING FOR THE ENVIRONMENTAL IMPACT ASSESSMENT OF TIDAL TURBINE ARRAYS	5015
<i>Marmo Brett</i>	
A STANDARD FOR THE MEASUREMENT OF UNDERWATER SOUND RADIATED FROM MARINE PILE-DRIVING	5022
<i>Robinson Stephen, Theobald Peter</i>	
SEABED VIBRATION - NOISE OR PROPAGATED SIGNAL?	5028
<i>Hazelwood Dick</i>	

IDENTIFICATION AND ASSESSMENT OF LONG TERM TRENDS IN UNDERWATER NOISE MEASUREMENTS	5035
<i>Sotirakopoulos Kostas, Harris Peter, Robinson Stephen, Wang Lian, Livina Valerie</i>	
EXPERIMENTAL INVESTIGATION OF NOISE SOURCES INSIDE AN UNDERWATER ROBOT\’S BUOYANCY VARIATION SYSTEM	5043
<i>Gafurov Salimzhan, Salmina Vera, Mukhametzyanov Andrey, Reshetov Viktor, Handroos Heikki, Greshnyakov Pavel</i>	
THE INVESTIGATION ON PREDICTION AND CALIBRATION OF LOW-FREQUENCY SOUND FIELD CHARACTERISTICS IN LARGE-SCALE NON-ANECHOIC POOL	5051
<i>Xing Junhua, Li Zhaozhui, He Xuesong</i>	

UNDERWATER ACOUSTICS MODELLING

ESTIMATION OF SOUND EXPOSURE LEVEL BASED ON RELATIVE MOVEMENT OF SHIP AND WHALE	5057
<i>Hirai Yukino, Tsuchiya Toshio, Shimizu Etsuro</i>	
MODELING OF PROPELLER-CAVITATION PULSE FOR ESTIMATING RECEIVED SOUND EXPOSURE LEVEL	5064
<i>Tsuchiya Toshio, Hirai Yukino, Shimizu Etsuro</i>	
A COMPARISON BETWEEN EXPERIMENTS AND SIMULATION FOR SHALLOW WATER SHORT RANGE ACOUSTIC PROPAGATION	5070
<i>Meyer Valentin, Audoly Christian</i>	

UNDERWATER ACOUSTIC MEASUREMENT PRACTICE

MEASUREMENTS OF UNDERWATER PILING NOISE DURING NEARSHORE WINDFARM CONSTRUCTION IN THE UK: POTENTIAL IMPACT ON MARINE MAMMALS IN COMPLIANCE WITH GERMAN UBA LIMIT	5078
<i>Ford Benjamin, Jiang Jian, Todd Victoria, Todd Ian</i>	
EFFECTS OF DEMODULATION METHODS ON THE REPRODUCTION OF UNDERWATER ACOUSTIC PRESSURE BY OPTICAL HETERODYNE INTERFEROMETRY	5086
<i>Wang Min, Yang Ping, He Longbiao, Feng Xiujuan, Xing Guangzhen, Zhang Yue</i>	

SHIP AND HARBOUR NOISE AND VIBRATION

EVALUATION OF AIRBORNE NOISE DUE TO NAVIGATION AND MANOEUVRING OF LARGE VESSELS	5094
<i>Fausti Patrizio, Bella Antonino Di, Guerra Maria Carmen, Santoni Andrea, Martello Nicolò Zuccherini</i>	
ON FIELD EXPERIMENTAL CHARACTERISATION OF THE SHIP SOURCES OF ACOUSTIC POLLUTION WITH-IN A COMMERCIAL HARBOUR	5100
<i>Viscardi Massimo, Siano Daniela, Rizzuto Enrico, Quaranta Franco, Coppola Tommaso</i>	
ON THE DIFFICULTIES IN MEASURING ACOUSTIC PARAMETERS ON-BOARD	5108
<i>Curletto Simone, Bo Vittorio</i>	
DEVELOPMENT OF A MECHANICAL SYNCHRONIZATION SYSTEM OF THE DIESEL GENERATORS IN ORDER TO MINIMIZE THE FORCES TRANSMITTED TO THE HULL	5115
<i>Lorenzo Francesco De, Iuliano Andrea, Tomas Adria Oliva, Marco Bruno Di, Heine Uwe</i>	
NONLINEAR VORTEX INDUCED VIBRATIONS OF INCLINED MARINE RISERS	5121
<i>Alfosail Feras, Nayfeh Ali, Younis Mohammad</i>	
THE TRANSFER PATH ANALYSIS METHOD OF SHIP VIBRATION AND EXPERIMENTAL RESEARCH	5129
<i>Li Ruibiao, Xu Rongwu, Mo Shiqi</i>	
RESEARCH ON THE DYNAMIC MODELING OF THE LONGITUDINAL VIBRATION OF A SHIP SHAFT-HULL SYSTEM	5140
<i>Chen Feng, Chen Yong, Hua Hongxing</i>	
STUDY ON THE INFLUENCE OF LIQUID FILM STIFFNESS ON SHAFTING VIBRATION UNDER MIXED LUBRICATION	5148
<i>Yang Guodong, Cao Yipeng, Zhang Wenping</i>	
EXPERIMENTAL STUDY ON VIBRATIONAL CHARACTERISTICS OF A RECTANGULAR BOTTOM PLATE IN CONTACT WITH FLUID	5156
<i>Wang Di, Wu Lei, Li Yueming</i>	
EXPERIMENTAL RESEARCH ON THE RESPONSES OF SHIP SHAFT UNDER LOADINGS ON BEARINGS	5161
<i>Zhang Cong, Qin Li</i>	
A NUMERICAL METHOD FOR ACOUSTIC INTERACTION WITH UNDERWATER STRUCTURES BASED ON NEAR-FIELD ARTIFICIAL BOUNDARY	5169
<i>Zhou Qidou, Huang ZhenWei, Wu ChongJian</i>	
LONGITUDINAL VIBRATION AND UNSTEADY THRUST TRANSMISSION OF THE RIM DRIVEN THRUSTER INDUCED BY INGESTED TURBULENCE	5177
<i>Chen Yong, Chen Feng, Long Xinhua</i>	

THE ANALYSIS OF VIBRATION CHARACTERISTIC OF COMBINATION FOUNDATION WITH COMPOSITE MATERIAL AND STEEL	5185
<i>Pan Chen</i>	

UNDERWATER NOISE AND ITS CONTROL

ON THE POSSIBILITY OF ESTIMATING SHIP PARAMETERS USING ACOUSTICAL LLOYD'S MIRROR EFFECT	5193
<i>Gaggero Tomaso, Traverso Federico</i>	
NOISE ANALYSIS AND CONTROL SCHEME OF UNDERWATER EXHAUST PROCESS	5201
<i>Miao Tiancheng, Wang Hao, Zhou Jian, Wu Dazhuan</i>	
OPTIMIZATION OF EXIT FLOW OF EXPANDING CAVITY WITH A FLOW-EQUILIBRATING DEVICE	5207
<i>Zhang Shiyang, Wu Chongjian, Ding Ziyou, Li Zhaoahui</i>	
AXIAL VIBRATION CONTROL OF PROPELLER SHAFTING SYSTEM USING DYNAMIC ANTI-RESONANT VIBRATION ISOLATOR	5215
<i>Liu Niuniu, Dong Xingjian, Hua Hongxing</i>	
RESONANCE-COUPLING EFFECT ON BROAD BAND GAP FORMATION AND SOUND ABSORPTION IN LOCALLY RESONANT SONIC METAMATERIALS.....	5223
<i>Wang Yuren, Jiang Heng, Chen Meng, Guo Yanhong</i>	

PREDICTIVE METHODS FOR UNDERWATER NOISE

MANAGEMENT OF ENVIRONMENTAL SUSTAINABILITY OF PORTS - FOCUS ON NOISE MITIGATION	5231
<i>Walid Kamali</i>	
ACOUSTICAL RADIATION PREDICTION FROM SPARSE VIBRATION SAMPLING	5238
<i>Mao Rongfu, Zhu Haichao, Su Changwei</i>	
VIBROELASTIC MODELS FOR FLOW NOISE ESTIMATION	5246
<i>MacGillivray Ian, Skvortsov Alex, Dylejko Paul</i>	
MACHINERY RADIATED NOISE EVALUATION OF UNDERWATER STRUCTURE WITH SPARSE SENSORS	5254
<i>Guo Cheng, Li Ruibiao, He Lin, Xu Rongwu</i>	
ACOUSTIC TIME-FREQUENCY PREDICTION SIMULATION METHOD IN SHIP STRUCTURE	5262
<i>Pang Fuzhen, Li Shuo, Xiong Yeping, Li Haichao</i>	

THE ACOUSTICS OF LIGHTWEIGHT BUILDINGS

MULTI-CRITERIA OPTIMIZATION OF A WOOD BASED FLOOR	5270
<i>Coguenanff Corentin, Guigou-Carter Catherine</i>	
LIGHTWEIGHT FLOOR : STEP BY STEP COMPARISONS BETWEEN MEASURED AND SIMULATED QUANTITIES	5278
<i>Coguenanff Corentin, Guigou-Carter Catherine, Späh Moritz</i>	
RAIN NOISE FROM AGRICULTURAL ROOFING.....	5286
<i>Demagnet Cyrille, Dubois Alexis, Fehr Bernd, Moore James, Smedt Joke De</i>	

BUILDING ACOUSTICS REGULATION AND CLASSIFICATION

STUDY ON SUBJECTIVE RESPONSES ACCORDING TO FACILITY EQUIPMENT NOISE IN APARTMENTS	5292
<i>Shin Hye-Kyung, Kim Kyoung-Woo, Jeong A-Yeong, Yang Kwan-Seop</i>	

VOLUME 8

ACOUSTIC CLASSIFICATION SCHEME AND DESIGN PROCEDURE FOR BUILDINGS PERTINENT TO INDUSTRIAL PREMISES FOR ENGINEERING OPTIMIZATION PURPOSES	5297
<i>Squadrone Giuseppe, Bacchi Elisa</i>	
EVALUATION OF IMPACT SOUND INSULATION FROM 20 HZ.....	5305
<i>Ljunggren Fredrik, Simmons Christian, Öqvist Rikard</i>	
CLASSIFICATION SCHEMES WITH HIGH-FREQUENCY IMPACT NOISE RATING (HIR).....	5310
<i>Dong Wayland, LoVerde John</i>	

STRUCTUREBORNE AND IMPACT SOUND IN BUILDINGS

PREDICTION OF NOISE FROM MACHINERY IN TIMBER-FRAME BUILDINGS USING TRANSMISSION FUNCTIONS.....	5316
<i>Schöpfer Fabian, Hopkins Carl, Mayr Andreas R., Schanda Ulrich</i>	

PREDICTING STRUCTURE-BORNE NOISE FROM BUILDING SERVICE EQUIPMENT USING AN IMPACT NOISE CALCULATION MODEL	5324
<i>Bailhache Simon, Villot Michel</i>	
LOW FREQUENCY STRUCTURE-BORNE SOUND POWER MEASUREMENTS USING HEAVYWEIGHT RECEPTION PLATES.....	5330
<i>Reinhold Steffi, Hopkins Carl, Zeitler Berndt</i>	
CHARACTERISATION OF SOURCES INJECTING A MOMENT POWER WITH THE TWO-STAGE-METHOD	5338
<i>Vogel Albert, Kornadt Oliver, Wittstock Volker, Voelker Conrad</i>	
DESIGN OF A TUNEABLE DAMPED SPRING SYSTEM FOR GYM TREADMILL ISOLATION	5346
<i>Cosstick Lloyd, Mitchell Andrew, Murray Timothy</i>	
PREDICTED EFFICIENCY OF VIBRATION ISOLATORS FOR EQUIPMENT INSTALLED IN HEAVYWEIGHT AND LIGHTWEIGHT CONSTRUCTIONS	5354
<i>Bailhache Simon, Dépierre Clément, Picard Nicolas</i>	
BUILDING COMPONENTS AND MATERIALS FOR LOW FREQUENCY STRUCTURE-BORNE AND AIRBORNE SOUND INSULATION	5362
<i>Alessandro Schiavi, Andrea Prato, Jean-Christophe Vallée</i>	
EXPERIMENTALLY BASED STATISTICAL ANALYSIS OF THE VIBRATIONAL ENERGY OF CLT BUILDING ELEMENTS.....	5370
<i>Mecking Simon, Scheibengraber Markus, Kruse Tobias, Schanda Ulrich, Wellisch Ulrich</i>	
ACOUSTIC PERFORMANCE PREDICTION FOR WOOD FRAME BASED FLOOR	5378
<i>Guigou-Carter Catherine, Coguenanff Corentin</i>	
ON THE RELEVANCE OF IMPACT SOURCE IMPEDANCE AT LOW FREQUENCIES - PART 2: FLOORS WITH FLOATING TOPPINGS	5386
<i>Zeitler Berndt, Schneider Martin, Sabourin Ivan</i>	
MEASUREMENT UNCERTAINTY IN SOUND INSULATION TESTING: COMPARISON OF FIELD TEST DATA FOR SEPARATING FLOORS	5394
<i>Whitfield Bill, Gibbs Barry</i>	
PREDICTION OF IMPACT SOUND INSULATION WITH A HYBRID FINITE ELEMENT-STATISTICAL ENERGY ANALYSIS APPROACH.....	5402
<i>Wang Pengchao, Dijkmans Arne, Lombaert Geert, Reyniers Edwin</i>	
IMPACT ISOLATION OF LIGHTWEIGHT GYM FLOORS USING 25 AND 50KG WEIGHTS	5410
<i>Hong Evan, Cosstick Lloyd, Murray Timothy, Hall Gary</i>	
COMPARING LABORATORY IMPACT SOUND DATA TO CALCULATED PREDICTION OF AIR STIFFNESS RESONANCE.	5418
<i>Byrick Wilson, Golden Matthew</i>	
LABORATORY EXPERIMENTS AND MODAL MODEL OF IMPACT SOUND TRANSMISSION THROUGH A LIGHTWEIGHT WOODEN FLOOR.....	5423
<i>Qin Yi, Hornikx Maarten, Bron Susanne, Koopman Arnold</i>	
MEASUREMENT OF LATERAL IMPACT NOISE ISOLATION	5431
<i>LoVerde John, Wayland Dong</i>	
DEVELOPMENT OF A RATING FOR EVALUATING THE IMPROVEMENT IN HIGH-FREQUENCY IMPACT ISOLATION	5438
<i>LoVerde John, Dong Wayland</i>	
EXPERIMENTAL STUDY ON VIBRATION CONTROL OF A BEAM-LIKE FOOTBRIDGE BY TUNED MASS DAMPER	5445
<i>Xie Weiping, Feng Jinpeng, He Wei</i>	

PREDICTION OF SOUND TRANSMISSION IN BUILDINGS

AN INVERSE FORM OF TRANSIENT STATISTICAL ENERGY ANALYSIS TO DETERMINE THE TRANSIENT POWER INPUT WITH FLOATING FLOOR SYSTEMS.....	5452
<i>Hirakawa Susumu, Hopkins Carl, Lee Pyoung Jik, Seiffert Gary</i>	
VIBRATION REDUCTION INDICES OF CROSS LAMINATED TIMBER JUNCTIONS.....	5460
<i>Timpte Aline, Mecking Simon, Schanda Ulrich, Rabold Andreas</i>	
EFFICIENT SOUND INSULATION PREDICTION MODELS FOR PLASTERBOARD WALLS	5468
<i>Wyngaert Jan Van Den, Schevenels Mattias, Reyniers Edwin</i>	
ROBUST ESTIMATION OF THE ENERGY FLOW IN TIMBER STRUCTURES.....	5476
<i>Winter Christoph, Buchschmid Martin, Müller Gerhard</i>	
APPARENT SOUND INSULATION IN COLD-FORMED STEEL-FRAMED BUILDINGS	5484
<i>Holler Christoph, Quirt David, Zeitler Berndt, Sabourin Ivan</i>	
FLANKING TRANSMISSION THROUGH STEEL-CONCRETE COMPOSITE FLOORS AND LIGHTWEIGHT PARTITIONS.....	5492
<i>Paxton Beth, Harvie-Clark Jack</i>	
DETAILED ANALYSIS OF MEASUREMENT RESULTS OF FLANKING TRANSMISSION ACROSS A JUNCTION COMPOSED OF DOUBLE WALLS CARRIED OUT ON A HALF SCALED TEST BENCH.....	5500
<i>Crispin Charlotte, Mertens Christian, Dijkmans Arne</i>	

FINITE DIFFERENCE TIME DOMAIN MODELLING OF SOUND RADIATION FROM A POINT-EXCITED ELASTIC PLATE INTO A REVERBERANT SPACE.....	5508
<i>Ferreira Nuno, Hopkins Carl</i>	
TIME-DOMAIN STRUCTURAL VIBRATION SIMULATIONS BY SOLVING THE LINEAR ELASTICITY EQUATIONS WITH THE DISCONTINUOUS GALERKIN METHOD.....	5516
<i>Sihar Indra, Hornikx Maarten, Pranowo</i>	
VIBRATION TRANSMISSION BETWEEN STACKED REINFORCED-CONCRETE BEAMS USING MONTE CARLO SIMULATIONS WITH FINITE ELEMENT METHODS.....	5524
<i>Filippoupolitis Marios, Hopkins Carl, Au Siu-Kui</i>	
AN EFFICIENT NUMERICAL APPROACH TO EVALUATE THE SOUND INSULATION OF ACOUSTIC METASURFACE	5531
<i>Yu Xiang, Cui Fangsen, Lu Zhenbo</i>	

MEASUREMENT OF SOUND INSULATION

THE SPATIAL VARIABILITY OF RANDOM NOISE IN A REVERBERANT SPACE	5536
<i>Davy John Laurence</i>	
MEASUREMENT UNCERTAINTY OF FAÇADE SOUND INSULATION: A COMPARISON BETWEEN ANOVA AND RRT UNCERTAINTY EVALUATIONS.....	5544
<i>Scrosati Chiara, Scamoni Fabio, Whitfield William, Gibbs Barry</i>	
AIRBORNE SOUND INSULATION: A STUDY ON THE CORRELATION BETWEEN 1/3 OCTAVE BAND VALUES AND ITS IMPACT ON THE RESULTING SNQ UNCERTAINTY	5552
<i>Monteiro Carolina, Borin Marcel, Machimbarrena Maria, Shimote Mariana</i>	
PARAMETERS MEASUREMENT OF TAPPING MACHINE AND ITS ACOUSTIC CHARACTERISTICS	5560
<i>He Longbiao, Kang Jian, Niu Feng, Feng Xiujuan, Yang Ping</i>	
A BLOCKED PRESSURE BASED TRANSFER PATH ANALYSIS (TPA) METHOD TO MEASURE THE SOUND INSULATION PATH CONTRIBUTIONS OF A PARTITION SUBJECTED TO AN INCIDENT AIRBORNE FIELD	5566
<i>Patil Nikhilesh, Elliott Andy, Moorhouse Andy</i>	
RADIATION EFFICIENCY OF METAL STUD PLASTER-BOARD WALLS	5574
<i>Schneider Martin, Zeitler Berndt</i>	
SOUND REDUCTION INDEX OF DRY-WALL MATERIALS: EXPERIMENTAL COMPARISON OF MODEL PREDICTIONS AND TRANSMISSION ROOM MEASUREMENTS	5581
<i>Piana Edoardo, Granzotto Nicola, Bella Antonino Di</i>	
IMPROVEMENT OF SOUND INSULATION PERFORMANCE OF WALLS, WINDOWS AND DOORS	5589
<i>Jeong A-Yeong, Kim Kyoung-Woo, Shin Hye-Kyung, Yang Kwan-Seop</i>	

PRACTICAL ASSESSMENTS OF UNCERTAINTY IN VIBRATION ISOLATION AND TRANSMISSIBILITY

MANAGING UNCERTAINTY WHEN PREDICTING RAIL-INDUCED GROUND BORNE NOISE AND VIBRATION	5597
<i>D'Avillez Jorge</i>	
EVALUATING UNCERTAINTY IN THE PREDICTION OF THE PERFORMANCE OF BASE-ISOLATION SYSTEMS DESIGNED TO REDUCE GROUNDBORNE NOISE IN BUILDINGS	5605
<i>Thornely-Taylor Rupert</i>	
VIBRATION MODELLING AND PERFORMANCE EVALUATION OF SPECIALIST BUILDINGS: A DESIGNER'S APPROACH	5612
<i>Karatsovis Christos, Smith Malcolm</i>	
THE USE OF TRIAL PILES IN ASSESSMENTS OF GROUNDBORNE VIBRATION	5619
<i>McNulty Martin</i>	
FROM ACOUSTIC SPECIFICATION TO HANDOVER. A PRACTICAL APPROACH TO AN EFFECTIVE AND ROBUST SYSTEM FOR THE DESIGN AND CONSTRUCTION OF BASE (VIBRATION) ISOLATED BUILDINGS.....	5627
<i>Farrell Oliver</i>	
A DETAILED, TRI-AXIAL MEASUREMENT AND MODELLING STUDY OF THE PERFORMANCE OF A BASE ISOLATED BUILDING IN LONDON DESIGNED TO PREVENT STRUCTURE BORNE NOISE AND VIBRATION FROM UNDERGROUND TRAINS	5635
<i>Galikowski Tomasz, Clarke David, Farrell Oliver</i>	

A HOLISTIC APPROACH TO ACOUSTICAL DESIGN IN ARCHITECTURE

GETTING GOOD SOUND ENVIRONMENT IN OLD BRICK AND WOOD STRUCTURE BUILDINGS.....	5643
<i>Zhang Sanming, Chen Linbing, He Haixia</i>	
AURAL DIFFERENCES OF ELEMENTARY ARCHITECTURAL CONFIGURATIONS: A COMPARATIVE TABLE.....	5651
<i>Ilias Papageorgiou</i>	

THE ACOUSTIC DESIGN OF THE UNIVERSITY OF SALFORD PERFORMING ARTS BUILDING	5659
<i>Robinson Matthew, Brown Una, Howarth Mark</i>	

FACADE SOUND INSULATION AND INTERNAL ENVIRONMENTAL QUALITY (IEQ)

DESIGN GUIDE FOR NOISE, VENTILATION AND OVERHEATING IN RESIDENTIAL DEVELOPMENTS	5666
<i>Chilton Anthony, Healey James, Hyden Matthew, Harvie-Clark Jack, Trew David, Conlan Nick</i>	
METHODS OF CONTROLLING NOISE LEVELS AND OVERHEATING IN RESIDENTIAL BUILDINGS	5674
<i>Conlan Nick, Harvie-Clark Jack</i>	
NOISE, VENTILATION AND OVERHEATING IN RESIDENTIAL DEVELOPMENTS	5682
<i>Waddington David, Fitton Richard, Bailey Will, Swanborough Huw, Thompson Catherine</i>	
ATTEMPTING TO TAYLOR SUIT THE FACADE SOUND INSULATION TO THE NEEDS OF THE OCCUPANTS	5689
<i>Asselineau Marc, Gaulupeau Aline</i>	
PERCEPTION OF RESIDENTS ON ACOUSTICALLY IMPROVED FACADE	5693
<i>Paris-Newton Juliette, Masson Florent</i>	
FURTHER DEVELOPMENT OF VENTILATION WINDOW	5699
<i>Cui Fangsen, Yu Xiang, Zhang Qide, Yao Kui</i>	
SPECTRAL VARIATION OF SOUND TRANSMISSION LOSS ACROSS PLENUM WINDOWS WITH NON-PARALLEL GLASS PANES	5705
<i>Tang S K</i>	
ACTIVE NOISE MITIGATION WITH TRANSPARENT PIEZOELECTRIC FILM SPEAKERS	5711
<i>Yao Kui, Mirhsekarloo Meysam Sharifzadeh, Tan Chin Yaw, Zhang Lei, Chen Shuting, Lai Szu Cheng, Cui Fangsen, Yu Xiang</i>	
ALTERNATIVES TO UK NOISE INSULATION REGULATIONS	5719
<i>Lawrence Adam, Betts Duncan, Boote Dan, Ahmad Nafis</i>	
AN ORIGINAL FRAMEWORK FOR ROAD TRAFFIC NOISE CONTROL IN CHINA BASED ON TRAFFIC VOLUME CHARGES/TAXES AND PUBLIC PARTICIPATIONS	5727
<i>Zhang Jiping, Zhang Lei, Zhang Xin, Zhang Liuqing</i>	

END- TRANSPOSITION AND IMPLEMENTATIONS OF CNOSSOS-EU

CNOSSOS-NL: ISSUES FOR NATIONAL IMPLEMENTATION OF THE EU ROAD NOISE EMISSION MODEL	5735
<i>Peeters Bert</i>	

RESEARCH INFORMED TEACHING IN ACOUSTICS

DO PERFORMANCE MUSICIANS NEED ACOUSTIC EDUCATION ?	5743
<i>Gomez-Agustina Luis, Reigersberg Muriel Swijghuisen</i>	

LIFE NEREIDE – EU PROJECT

LIFE NEREIDE: INNOVATIVE MONITORING ACTIVITIES ON IMPLEMENTATION URBAN SITES	5751
<i>Licitra Gaetano, Cerchiai Mauro, Chiari Claudia, Ascari Elena</i>	
ON SITE DETERMINATION OF SOUND ABSORPTION COEFFICIENT OF ROAD PAVEMENTS USING MOBILE LABORATORY	5759
<i>Castro Fabio Lo, Iarossi Sergio, Luca Massimiliano De, Ascari Elena, Stanzial Domenico, Licitra Gaetano</i>	
LIFE NEREIDE: NEW LOW NOISE PAVEMENT SURFACES	5767
<i>Leandri Pietro, Losa Massimo, Rocchio Patrizia</i>	
THE ULTRA LOW NOISE POROELASTIC ROAD SURFACE: A REAL LIFE DEMONSTRATION IN THE LIFE PROJECT NEREIDE	5775
<i>Goubert Luc</i>	

NATIONAL AND INTERNATIONAL NOISE POLICY, GUIDANCE, STANDARDS AND PROJECTS

NOISE POLICY STATEMENT FOR ENGLAND - 7 YEARS ON	5783
<i>Turner Stephen, Grimwood Colin</i>	
FUTURE PERMITTING, REGULATION, AND CONTROL OF NOISE FROM INDUSTRY AFTER THE UNITED KINGDOM LEAVES THE EUROPEAN UNION	5791
<i>Clayton Tony, Tofts Jon, Waddington David</i>	
TOOLKIT FOR ASSESSING COSTS AND BENEFITS OF NOISE MITIGATION MEASURES	5797
<i>Lawrence Adam, Ekici Inan, Boote Dan</i>	
INTRODUCTION AND MANAGEMENT OF NOISE LOW EMISSION ZONES: LIFE MONZA PROJECT	5805
<i>Luzzi Sergio, Bellomini Raffaella, Borchhi Francesco, Curcuruto Salvatore, Silvaggio Rosalba, Nizzola Carlo, Carfagni Monica, VolpeYary, Arcangeli Giulio</i>	

PROPOSAL FOR AN IN SITU APPROVAL TESTING AND QUALITY ASSURANCE PROCEDURE FOR ASSESSING SOUND REFLECTION PROPERTIES OF NOISE BARRIERS	5811
<i>Fuchs Andreas, Wehr Reinhard, Conter Marco</i>	

EUROPEAN DOCTORAL TRAINING IN AEROACOUSTICS BY A MARIE CURIE INTEGRATED TRAINING NETWORK	5818
<i>Rona Aldo, Hall Edward, Puigt Guillaume, Camussi Roberto, Schram Christophe, Airiau Christophe, Felli Mario, Lai Choi-Hong</i>	

SOUND RADIATION FROM MUSICAL INSTRUMENTS

REAL-TIME PHYSICAL MODEL OF AN AEOLIAN HARP	5826
<i>Selfridge Rod, Moffat David, Reiss Joshua, Avital Eldad</i>	
VIBRO-ACOUSTICS OF THE SOUTH INDIAN DRUM: MRIDANGAM	5834
<i>Sooraj G, Padmanabhan Chandramouli</i>	
APPLICATION OF SINUSOIDAL CURVES TO SHAPE DESIGN OF CHORD SOUND PLATE AND EXPERIMENTAL VERIFICATION	5842
<i>Wang Bor-Tsuen, Hsu Yong-Shiang, Cheng Shao-Wei, Chen Chian-Hong, Huang Chia-Hsien, Wu Ying-Hui</i>	

SOUND PERCEPTION OF MUSICAL INSTRUMENTS

THE APPLICATION OF PETUNG BAMBOO FOR GUITAR TOP PLATE AND THE PERCEPTION OF ITS ACOUSTIC QUALITY	5850
<i>Kusumaningtyas Indraswari, Prasetyo Heru Dwi, Purwanto Toby Anindyajati</i>	
SUBJECTIVE PREFERENCE OF ELECTRIC GUITAR SOUNDS IN RELATION TO PSYCHOACOUSTICAL AND AUTOCORRELATION FUNCTION PARAMETERS.....	5858
<i>Leguizamón Diego, Masson Florent, Sato Shin-ichi</i>	
THE ELUCIDATION OF ANCIENT GREEK HARMONIA MODE – HETERODYNE RESONANCE	5866
<i>Ito Ken</i>	
SEPARATION OF STRUCTURAL TIMBRE AS NARROWBAND DIGITAL PROXIMAL SINUSOIDAL SPIKES	5873
<i>Ito Ken, Takei Akinori</i>	
POSSIBLE ORIGIN OF MINOR TRIADS FROM HETERODYNE RESONANCE BETWEEN PORTAMENTI	5881
<i>Ito Ken, Takei Akinori</i>	

MUSICAL INSTRUMENTS IN PERFORMING SPACES

AN INVESTIGATION INTO THE EFFECT OF ACOUSTICS ON VOCAL STRAIN OF OPERA SINGERS	5888
<i>Okten Gizem, Dance Stephen</i>	
PRESSURE FIELDS IN THE VICINITY OF BRASS MUSICAL INSTRUMENT BELLS MEASURED USING A TWO DIMENSIONAL GRID ARRAY AND COMPARISON WITH MULTIMODAL MODELS	5896
<i>Kemp Jonathan, Lopez-Carromero Amaya, Campbell Murray</i>	
FDTD SIMULATION OF A HYBRID 1D/3D BRASS INSTRUMENT MODEL AND COMPARISON TO MEASURED RADIATION DATA	5904
<i>Harrison Reginald Langford, Hamilton Brian, López-Carromero Amaya</i>	

POSTER SESSION PAPERS

VARIATIONS WITHIN SIMPLE MODELS FOR STRUCTURE-SOIL INTERACTION	5911
<i>Andersen Lars, Bucinskas Paulius, Peplow Andrew</i>	
ULTRASOUND PROPAGATION IN THE MARTIAN ATMOSPHERE	5917
<i>Lin Weijun, Jia Yang, Li Chao, Xue Bo, Zhang Jingchuan, Cui Hanyin</i>	
EXPERIMENTS OF SPEED OF SOUND IN THE LOW PRESSURE ATMOSPHERE OF MARS	5921
<i>Jia Yang, Lin Weijun, Xue Bo, Li Chao, Zhang Jingchuan, Cui Hanyin</i>	
ANALYSIS AND VALIDAATIONS OF OPTICAL IMAGE STABILIZATION ACTUATOR FOR CELLPHONE CAMERA MODULES.....	5925
<i>Hsieh Chang-Lin, Wang Hsiao-Yu, Chang Yu-Hao, Liu Chien-Sheng</i>	
PREDICTION AND ANALYSIS OF FRICTION-INDUCED NOISE IN ELASTOMERIC BEARINGS	5932
<i>Zhang Neng, He Lin, Yang Xue</i>	
STUDY ON THE BAFFLED EFFECT OF MOBILE PHONE PANEL	5940
<i>Liu Yu-Cheng</i>	
HIGH-SPEED TRAIN NOISE SOURCE HEIGHT INFLUENCE ON EFFICIENCY OF NOISE BARRIERS	5947
<i>Ivanov Nickolay, Shashurin Aleksander, Boiko Iuliia, Rudakov Marat, Tyurina Natalia</i>	
THICKNESS, DENSITY AND POROSITY RELATIONSHIP TOWARDS SOUND ABSORPTION PERFORMANCE OF MIXED PALM OIL FIBERS	5952
<i>Samsudin Emedya Murniawaty, Ismail Lokman Hakim, Kadir Aeslina A., Nasidi Ida Norfaslia</i>	
FUEL INJECTION PUMP PHASING EFFECT ON GEAR-TRAIN IMPACT NOISE OF DIESEL ENGINES	5960
<i>Tatar Ali, Karaca Cigdem, Subasi Osman, Sanliturk Kenan Y.</i>	

RESEARCH ON RAIL CORRUGATION BASED ON STANDING WAVE THEORY	5968
<i>Xu Ning, Wang Anbin</i>	
SIGNAL TO NOISE RATIO OF THE SIGNAL SOUND AND ANNOUNCEMENT IN SUBWAY STATION	5975
<i>Ryu Jongkwan, Jin Mingyu, Sung Changju, Song Hansol, Oh Yangki, Song Minjung, Park Hyungu</i>	
GYM FLOORING – DESIGNING FOR IMPACT AND PREDICTION	5980
<i>Fox Adam, McNulty Martin</i>	
THE FORMATION OF THE SPIRAL GAS-DYNAMIC FLOW IN THE FIELD OF STANDING ACOUSTIC WAVE	5988
<i>Gogbunova Anastasiya, Molevich Nonna, Zavershinskii Igor, Zavershinskii Dmitrii</i>	
USING GAUSSIAN PROCESSES TO MODEL COMBUSTION DYNAMICS	5994
<i>Matthaiou Ioannis, Khandelwal Bhupendra, Antoniadou Ifigeneia</i>	
THEORETICAL AND EXPERIMENTAL STUDY OF A VIBRATION ISOLATOR USING A NEGATIVE STIFFNESS MAGNETIC SPRING	6002
<i>Zheng Yisheng, Zhang Xinong, Xie Shilin, Zhang Yahong</i>	
A PARALLEL ACTIVE ORDER SOUND EQUALIZATION METHOD TO IMPROVE VEHICLES SOUND QUALITY DURING ACCELERATION	6009
<i>Wang Yu, Liao Xiangning, Qi Songming, Zheng Sifa</i>	
REVIEW OF THE WORKS ON THE EFFECT OF SOUND ON OFFICE PRODUCTIVITY	6017
<i>Mak Cheuk Ming, Wong Hai Ming, Kang Shengxian, Ou Dayi</i>	
EXPERIMENTAL STUDIES OF ACOUSTIC PROPAGATION CHARACTERISTICS IN THE LOW PRESSURE OF CO₂ ATMOSPHERE BASED ON THE FIBER OPTICAL SENSING TECHNOLOGY	6023
<i>Zhang Jingchuan, Wang Jing, Li Chao, Cui Hanyin</i>	
APPLICATION OF ADDED MASS CONCEPT OF BENDING VIBRATION TO THE DESIGN OF A LEVEL SWITCH SENSOR	6031
<i>Kim Jinoh, Hwang JeongGil, Seon Sangok, Piao Chunguang</i>	
EVALUATION OF VIBRATION IN TURBOMACHINERY FOR SUPERCRITICAL CO₂ SYSTEM SUPPORTED BY HYBRID MAGNETIC BEARINGS	6039
<i>Park Cheol Hoon, Park Jun Young, Yoon Eui Soo</i>	
PREDICTION OF TEMPERATURE DEPENDENT WAVE DISPERSION AND INTERACTION PROPERTIES IN COMPOSITE STRUCTURES	6047
<i>Apalowo Rilwan, Ampatzidis Theofanis, Chronopoulos Dimitrios, Ichchou Mohammed, Yasser Essa, Escalera F. Martin De La</i>	
VOLUME 9	
PZT SENSORS BENCHMARKING AND A WAVELET TRANSFORM APPROACH FOR ACOUSTIC EMISSION SOURCE LOCATION	6055
<i>Martinez Ian, Marshall Matthew, Antoniadou Ifigeneia</i>	
STUDY OF BUBBLE FORMATION DYNAMICS BASED ON ASSOCIATED ACOUSTIC RADIATION	6063
<i>Chen Li, Norwood Chris, White Paul, Leighton Timothy</i>	
HIERARCHICAL PHONONIC CRYSTALS WITH BROAD BAND GAPS IN LOW FREQUENCY BY USING HOMOGENIZATION THEORY	6071
<i>Lee Kiyong, Jeon Wonju</i>	
A COMPARATIVE STUDY ON THE GRAVITATIONAL ACCELERATION CANCELLATION FROM ON-ROTOR MEMS ACCELEROMETERS FOR CONDITION MONITORING	6075
<i>Mones Z, Feng G, Tang X, Haba U, Gu F, Ball A D</i>	
SENSING OF CANCER DNA USING QUARTZ CRYSTAL MICROBALANCE	6083
<i>Park Chanho, Park Hyunjun, Na Sungsoo</i>	
EFFECTS OF DEVIATIONS OF A MONKEY SKULL'S ACOUSTIC PARAMETERS ON TRANSCRANIAL FOCUSED ULTRASOUND	6086
<i>Su Chang, Lin Weijun, Cui Hanyin, Wang Xiangda</i>	
THE INFLUENCE OF THE KERF WIDTH OF A PLANAR ARRAY ON THE TRANSCRANIAL FOCUSED ULTRASOUND FIELD	6093
<i>Wang Xiangda, Lin Weijun, Su Chang, Cui Hanyin</i>	
NONLINEAR DYNAMICS FOR AN AUTOMOTIVE WIPER SYSTEM	6100
<i>Chang Shun-Chang, Hu Jui-Feng</i>	
CHARACTERIZATION OF SHORT DURATION NOISE EVENTS FOR THE EVALUATION OF ANNOYANCE IN SCHOOLS EXPOSED TO TRAFFIC NOISE	6108
<i>Secchi Simone, Brambilla Giovanni, Casini David, Cellai Gianfranco</i>	
OPTIMIZATION DESIGN OF SOUND BARRIER WITH ABSORBING MATERIAL USING TOPOLOGY OPTIMIZATION	6116
<i>Chen Leilei, Zhao Wenchang</i>	
FACE THE MUSIC: A BEFORE AND AFTER STUDY OF THE HEARING ACUITY OF CLASSICAL MUSIC STUDENTS	6122
<i>Dance Stephen, Shearer Doug</i>	
AN ACOUSTIC FAULT SAMPLE EXPANSION METHOD BASED ON NOISE DISTURBANCE	6129
<i>Wei Na, Zhang Linke, Qiu Xiaojun</i>	
PERFORMANCE EVALUATION OF EXCAVATOR CABIN MOUNTING SYSTEM CONSIDERING NONLINEAR STIFFNESS CHARACTERISTICS	6135
<i>Kim Younghyun, Kim Raekwan</i>	

AN INVESTIGATION ON THE OPTIMIZATION OF AIR LAYERS AND POROUS ELASTIC MATERIALS FOR SOUND INSULATION OF COMPOSITE STRUCTURE	6141
<i>Bai Guofeng, Zhan Pei, Sui Fusheng, Yang Jun</i>	
THE MECHANISMS FOR AUDITORY ATTENTION TO ANNOYING-EVENT	6148
<i>Liang Yan, Wang Lei</i>	
ESTIMATION ON THE PROBABILITY DISTRIBUTION OF VON MISES STRESS FOR COMPLEX STRUCTURE UNDERGOING MULTIPLE-DIMENSIONAL RANDOM EXITATIONS	6152
<i>Huang Gangting, Xie Shilin, Zhang Xinong</i>	
IMPROVING THE LOW FREQUENCY SOUND TRANSMISSION LOSS OF DOUBLE-PANEL STRUCTURES WITH PERFORATED BALL SOUND ABSORBERS	6159
<i>Chang Daoqing, Li Dengke, Liu Bilong</i>	
STATE ESTIMATION METHOD FOR SOUND ENVIRONMENT BASED ON AN EXTENSION TYPE UKF BY CONSIDERING NON-GAUSSIAN NOISE	6165
<i>Orimoto Hisako, Ikuta Akira</i>	
MODAL CHARACTERISTICS ANALYSIS OF BLOCK AND CRANKSHAFT OF 18V32/40 DIESEL ENGINE FOR OFFSHORE PLATFORM POWER STATION	6173
<i>Yuan Ruiqi, Du Jingtao, Wu Dengfeng, Liu Zhigang</i>	
ACTIVELY CREATED QUIET ZONES USING DIRECTIONAL ARRAY OF LOUDSPEAKERS	6181
<i>Liu Jingwei, Wang Xiaolin, Wu Ming, Yang Jun</i>	
THE EFFECT OF COMPRESSOR OIL ON THE SPEED OF SOUND IN MULTIPHASE / MULTICOMPONENT FLOW OF A REFRIGERANT	6188
<i>Flieger Oliver, Tegethoff Wilhelm, Koehler Juergen</i>	
VIBRATION AND ACOUSTIC EMISSION MONITORING OF A GIRTH WELD DURING A RESONANCE FATIGUE TEST	6196
<i>Shamsudin Mohd Fairuz, Johnston Carol, Mares Cristinel, Edwards Graham, Gan Tat-Hean</i>	
SELF-OSCILLATING MODELS OF THE TONGUE TIP FOR SIMULATING ALVEOLAR TRILLS	6204
<i>Elie Benjamin, Laprie Yves</i>	
RESEARCH ON ISOLATION EFFECT OF VIBRATION ISOLATION TRENCH IN SOIL MEDIUM BY 1:50 MODEL TEST	6212
<i>He Lei, Wu Yubin, Wu Dan, Wu Yanan, Song Ruixiang, Hu Wencheng</i>	
WHY RESEARCH INFORMED TEACHING (RIT) IN ACOUSTICS EDUCATION: HOW CAN WE EMBED RESEARCH IN ACOUSTICS EDUCATION TO IMPROVE STUDENTS LEARNING?	6220
<i>Aygün Haydar</i>	
INFLUENCE OF BOUNDARY RESTRAINING STIFFNESS ON VIBRATION CHARACTERISTICS OF CONICAL SHELL STRUCTURE MADE OF FUNCTIONALLY GRADED MATERIAL	6227
<i>Xing Xue, Li Wenda, Du Jingtao, Liu Zhigang</i>	
ACOUSTIC MODE ANALYSIS OF ENCLOSE FLUID WITH INTERNAL FLEXIBLE STRUCTURE	6235
<i>Li Pei, Li Honggang, Sun Guocang, Lei Chengyou</i>	
EXPERIMENTAL STUDY ON THE ELECTROMAGNETIC ACTUATOR-AIR SPRING VIBRATION ISOLATOR	6241
<i>Ma Jianguo, Shuai Changgeng, Li Yan</i>	
COMPUTATIONAL INVESTIGATION OF DIRECT NOISE GENERATED BY SYNTHETIC HOT SPOTS IN A DUCT	6248
<i>Rodrigues Jocelino, Rolland Erwan O., Domenico Francesca De, Hochgreb Simone</i>	
NOISE REDUCTION PROGRAM FOR EMPLOYEE EXPOSURE IN WORKPLACE	6256
<i>Papa Augusto</i>	
EXPERIMENTAL STUDY OF THE EFFECT OF FLOW VELOCITY AT THE INLET ON THE AZIMUTHAL MODE RADIATION: STATIC AND FLIGHT	6264
<i>Ostrikov Nikolay, Yakovets Mikhail, Ipatov Maksim, Pankratov Ivan, Denisov Stanislav</i>	
ACOUSTIC COMFORT IN EDUCATIONAL BUILDINGS: LITHUANIAN CASE STUDY	6272
<i>Masiulyte-Vitkauskė Liepa, Bogdaniene Egle Ganda, Jagniatinskis Aleksandras, Mickaitis Marius, Lebednykaite Migle</i>	
DESCRIPTION AND ANALYSIS OF ELASTIC WAVES IN FUNCTIONALLY GRADED MATERIALS	6278
<i>Bednarik Michal, Cervenka Milan</i>	
EXPERIMENTAL STUDY ON LINEAR QUADRATIC ALGORITHMS IN ACTIVE VIBRATION ISOLATION SYSTEM	6284
<i>Kosenkov Peter, Makaryants George</i>	
NOISE CONTROL FOR A TANDEM AIRFOIL CONFIGURATION USING TRAILING EDGE SERRATION	6290
<i>Liu Xiao, Ali Syamir Bin Showkat, Azarpeyvand Mahdi</i>	
GEOMETRICAL ANALYSIS OF VIBRATIONS OF FUNCTIONALLY GRADED SHELL PANELS USING THE R-FUNCTIONS THEORY	6298
<i>Shmatko Tetyana, Kurpa Lidiya, Bhaskar Atul</i>	
CATEGORIZATION OF THE BATS SPECIES BASED ON EIGEN ANALYSIS OF BAT BIOSONAR BEAM PATTERN	6306
<i>He Weikai, Feng Jianxiang, Gao Li</i>	
AN EXPERIMENTAL INVESTIGATION INTO THE NOISE OF A CONTINUOUS POSITIVE AIRWAY PRESSURE DEVICE	6313
<i>Gu Yiwen, Islam Md Nifarul, Konka Harshavardhan, McCooey Conor, Wang Xu</i>	
DYNAMIC INSTABILITY CHARACTERISTICS OF ROLLING ELEMENT BEARINGS	6321
<i>Panat Sreedath, Puliyeril Baldev, Ramagiri Srinath, Sarkar Abhijit</i>	

VIBRATION ISOLATION ANALYSIS OF THE SUBWAY STATION USING A SEMI-EXPERIMENT AND SEMI-NUMERICAL METHOD	6329
<i>Liu Changqing, Zhu Wenyong, Xia Dan, Sun Xiaoming</i>	
IMPLEMENTATION OF ACOUSTIC CONTRAST CONTROL BETWEEN THE SEATS IN A CAR CABIN-LIKE ROOM USING LOUDSPEAKERS ON FLOOR.....	6336
<i>Lee Minho, Ryu Seokhoon, Kim Jeakwan, Lee Young-Sup, Lee Seungsu, Oh Sangjun</i>	
ANALYSIS OF THE VIBRATION ISOLATION BARRIER EFFECT FOR THE INDOOR ENVIRONMENT VIBRATION OF BUILD INDUCED BY RAIL TRANSIT	6338
<i>Wu Yanan, Wu Yubin, He Lei, Wu Dan, Song Ruixiang, Hu Wencheng</i>	
RESEARCH ON CHARACTERISTIC OF ANNOYANCE PERCEPTION OF LOW-FREQUENCY NOISES IN DENSELY POPULATED CITIES.....	6346
<i>Shao Zhiyue, Zhang Weichen, Zhou Yude, Zhu Wenyong</i>	
IDENTIFICATION OF MECHANICAL NOISE SOURCES BASED ON SUPPORT VECTOR DATA DESCRIPTION AND SEQUENTIAL BACKWARD SELECTION	6354
<i>Cui Li-lin, Zhu Hai-chao</i>	
PERSONAL ACTIVE CONTROL SYSTEMS OVER COUPLED NETWORKS	6361
<i>Antoñanzas Christian, Ferrer Miguel, Diego María De, Gonzalez Alberto</i>	
LOCALIZATION OF SOUND SOURCES IN TEMPERATURE INVERSION LAYER DURING A GEOMAGNETIC STORM	6369
<i>Laine Unto K.</i>	
SPOOL POSITION CONTROL OF PIEZOSTACK VALVE SYSTEM OPERATED AT VARIOUS TEMPERATURES.....	6377
<i>Han Chulhee, Hwang Yong-Hoon, Choi Seung-Bok</i>	
SOUND ABSORPTION OF MICRO-PERFORATED PANEL PRODUCED BY ADDITIVE MANUFACTURING	6382
<i>Liu Zhengqing, Fard Mohammad, Zhan Jiaxing, Davy John Laurence, Liu Xiaojing</i>	
IMPROVED LEAST-MEAN-SQUARE ALGORITHM USING A BLOCK-BASED STRATEGY FOR ACTIVE NOISE CONTROL	6390
<i>Fuster Laura, Ferrer Miguel, Diego Maria de, Antoñanzas Christian</i>	
MEASUREMENT DEVICE FOR VERTICAL SEISMIC PROFILING WHILE DRILLING	6398
<i>Gao Wenkai, Jia Hengtian, Zhang Lei, Ai Weiping, Sheng Limin, Dou Xiurong, Zhang Liancheng</i>	
VARIANCE OF SPECTRAL ENTROPY (VSE): AN SNR ESTIMATOR FOR SPEECH ENHANCEMENT IN HEARING AIDS	6404
<i>Liu Fangqi, Yasin Ifat, Demothénous Andreas</i>	
MEASURING OF BLAST-INDUCED GROUND VIBRATIONS; COMPARISON BETWEEN TWO DIFFERENT METHODS	6412
<i>Coltrinari Gianluca</i>	
ACTIVE NOISE SYSTEMS FOR REDUCING OUTDOOR NOISE	6420
<i>Borchi Francesco, Carfagni Monica, Lapini Alessandro, Argenti Fabrizio, Biagini Massimiliano, Fibucchi Leonardo</i>	
APPROACHES TO THE RAIL NOISE REDUCTION	6428
<i>Drozdzova Lyudmila, Butorina Marina, Kuklin Denis</i>	
DUCTED SILENCER TEST FACILITY WITH ADJUSTABLE TEST DUCT IN CHINA ACADEMY OF BUILDING RESEARCH.....	6436
<i>Wu Weibin, Xu Chun, Yan Guojun, Lin Jie, Ru Lyujing</i>	
STRUCTURAL ANALYSIS OF A LARGE VIBRATION TEST FACILITY FOR SPACE STATION	6442
<i>Liu Minghui, Cao Hui, Wang Jian, Gao Haiyang, Zhang Jungang, Yue Zhiyong</i>	
ROLE OF ULTRASOUND IN CELLULARPHONE HYGIENE.....	6450
<i>Sharma Meena, Sharma Neha</i>	
SHOCK ISOLATION PERFORMANCE OF A NOVAL QUASI-ZERO STIFFNESS DISPLACEMENT RESTRICTOR.....	6457
<i>Zhang Chunhui, Chen Ji</i>	
DESIGN AND IMPLEMENTATION OF AN ACTIVE NOISE AND VIBRATION CONTROL SYSTEM BASED ON OMAP ARCHITECTURE	6465
<i>Li Xin, Zhang Han, Cui Tianhao, Cheng Xiaobin, Yang Jun</i>	
EVALUATION OF VIBROACOUSTIC COMFORT IN MEANS OF PUBLIC TRANSPORT IN POZNAN ON THE BASIS OF SURVEY RESEARCH	6470
<i>Orczyk Malgorzata</i>	
INFLUENCE OF NOISE GENERATED BY MEANS OF TRANSPORT ON THE ENVIRONMENT	6478
<i>Orczyk Malgorzata, Tomaszewski Franciszek</i>	
MULTIPLE VIBRATION BAND GAPS IN LOCALLY RESONANT BEAM CARRYING SINGLE PERIODIC ARRAY OF CANTILEVER BEAM TYPE RESONATORS.....	6486
<i>Zhu Xuezhi, Chen Zhaobo, Jiao Yinghou</i>	
VIBRATION-BASED STRUCTURAL DAMAGE IDENTIFICATION USING DATA MINING	6494
<i>Meisam Gordan, Zubaidah Ismail, Hashim Abdul Razak, Zainah Ibrahim</i>	
ANALYSIS OF AUDIBLE NOISE AND VIBRATION TO DETECT DC-BIAS IN POWER TRANSFORMERS.....	6502
<i>Wu Xiaowen, Zhou Nianguang, Hu Sheng, Peng Jiwen, Lu Ling, Pei Chunming</i>	
A TIME-FREQUENCY COUPLING ANALYSIS METHOD FOR DATA FROM MICRO-VIBRATION GROUND-TESTING	6509
<i>Li Dong, Fan Shichao</i>	
OBJECTIVE THE EVALUATION METHOD OF CAR RIDE QUALITY	6515
<i>Park Yujin, Lee Sangkwon</i>	

THE EFFECT OF SOUND AND VIBRATION CHARACTERISTICS OF CFRP COMPOSITE PLATE ON INTERIOR NOISE BY CARBON FIBER LAMINATION ANGLE	6519
<i>Bang Sung Il, Lee Sang Kwon</i>	
OBJECTIVE EVALUATION OF THE SOUND QUALITY FOR ACCERLATING WARNING SOUND OF ELECTRIC VEHICLE BASED ON WHINE INDEX.....	6523
<i>Han Manuk, Lee Sang-Kwon</i>	
MATCHING LAYER DESIGN OF AN ULTRASONIC TRANSDUCER FOR WIRELESS POWER TRANSFER SYSTEM.....	6527
<i>Hwang Gunn, Youm WooSub, Lee Sung Q</i>	
ESTIMATION OF THE ABSORPTION PERFORMANCE OF POROUS MATERIAL/MPP COMPOUND STRUCTURE.....	6534
<i>Wang Yanpeng, Jiao Yinghou, Chen Zhaobo, Zhu Xuezhi</i>	
SPEECH PROPAGATION IN OPEN-PLAN OFFICE: A CROSS OVER DESIGNED FIELD STUDY	6542
<i>Davidsson Frans, Hodsman Paige</i>	
A PSYCHOLOGICAL APPROACH TO RESOLVING OFFICE NOISE	6551
<i>Davidsson Frans, Hodsman Paige, Oseland Nigel</i>	
VIRTUAL REALITY IN CHURCH ACOUSTICS: VISUAL AND ACOUSTIC EXPERIENCE IN THE CATHEDRAL OF SEVILLE, SPAIN	6561
<i>Álvarez-Morales Lidia, Molina-Rozalem Juan Francisco, Girón Sara, Alonso Alicia, Bustamante Pedro, Álvarez-Corbacho Ángel</i>	
CONTROL OF ACOUSTIC FIELD OF BACKWARD ACOUSTIC WAVES IN PIEZOELECTRIC PLATES.....	6569
<i>Kuznetsova Iren, Nedospasov Ilya, Qian Zhenghua, Wang Bin, Zhu Feng</i>	
INVESTIGATION OF AEROACOUSTICS PROBLEMS USING A DISCONTINUOUS GALERKIN SPECTRAL ELEMENT METHOD	6575
<i>Bao Zhenzhong, Qin Guoliang</i>	
DEVELOPMENT OF NANOBIOSENSORS BASED ON ACOUSTOELECTRONIC TECHNOLOGIES.....	6583
<i>Kolesov Vladimir, Anisimkin Vladimir, Kuznetsova Iren, Soldatov Eugenii, Dagesyan Sarkis, Melnikov Alexander, Kashin Vadim, Qian Zhenghua, Wang Bin, Zhu Feng</i>	
CALCULATION METHOD OF DYNAMIC CHARACTERISTICS OF FLOATING RAFT ISOLATION SYSTEM.....	6587
<i>Wang Qing, He Xuesong, Du Kun, Li Zhaohui</i>	
THE PLATFORM DESIGN FOR ANVC BASED ON KEYSTONE	6594
<i>Cui Tianhao, Cheng Jiahuan</i>	
VOICE ONSET TIME OF NATIVE- AND NON-NATIVE-ENGLISH SPEAKERS: A CASE STUDY OF BENGALI SPEAKERS	6600
<i>Tomita Kaoru</i>	
ACOUSTICAL BEHAVIOUR OF A PASSENGER CABIN OF A RO-PAX VESSEL	6606
<i>Borelli Davide, Gaggero Tomaso, Rizzuto Enrico, Schenone Corrado</i>	
A REVIEW OF THE METHODS FOR SOLVING THE ILL-CONDITIONED PROBLEM IN FREQUENCY DOMAIN IDENTIFICATION OF LOAD	6614
<i>Zeng Hui, Wu Xianjun, Chen Xia</i>	
VIBRATION TRANSFER PATH ANALYSIS BASED ON PSEUDO FORCE.....	6622
<i>Yan Weiguang, Wu Xianjun, Pan Yunping</i>	
AN AURALIZATION ETUDE FOR VOCAL ENSEMBLES USING ODEON.	6628
<i>Burns Thomas</i>	
THE DEVELOPMENT AND EXPERIMENTAL STUDY OF THE SOUND ABSORBERS MADE OF ACOUSTIC METAMATERIALS	6632
<i>Tomilina Tatiana, Grebennikov Aleksander, Laktionova Maria, Afanasev Kirill, Safin Artur, Vdovin Roman</i>	
MATHEMATICAL ESTIMATION AND EXPERIMENTAL STUDY OF THE BLADDER TYPE WATER MUFFLER	6637
<i>Wang Zhuang</i>	
VIBRATION AND SOUND RADIATION ANALYSIS OF PROPELLER-SHAFT-HULL COUPLED SYSTEM IN SURFACE VESSELS UNDER PROPELLER EXCITATION	6645
<i>Lei Zhiyang, Wang Chunxu, Wang Hao, Zhang Zhenhua, Hua Hongxing</i>	
ENLARGING THE SHORT RANGE DETECTION LIMIT USING INPUT SHAPING TECHNIQUE IN LOW DAMPING ULTRASONIC TRANSDUCERS	6653
<i>Lee Sung Q, Youm Woosub</i>	
STATISTICAL ANALYSIS USING SOUND PRESSURE LEVEL AND SOUND QUALITY METRICS ON ROTATING ELECTRICAL MACHINES FED BY PULSE WIDTH MODULATION.....	6659
<i>Jimenez-Romero Francisco Javier, Lara-Raya Ramon, Redel-Macías María Dolores</i>	
DETERMINING THE MECHANICAL PROPERTIES OF AMYLOID-LIKE NANOSHEETS BY APPLYING PLATE THEORY ON ITS ELASTIC NETWORK MODEL	6666
<i>Chang Hyun Joon, Lee Myeongsang, Kim Jae In, Yoon Gwonchan, Na Sungsoo</i>	
PIEZO-RESISTIVE CHARACTERISTICS OF CARBON BASED CEMENT MATERIALS	6670
<i>Rehman Sardar Kashif Ur, Ibrahim Zainah, Javed Mohammad Faisal, Hanif Muhammad Usman</i>	
STUDY ON THE RADIATED NOISE OF UNDERWATER TARGET BASED ON THE TEST MODEL OF IMPACT SYSTEM	6677
<i>Wu Wuhui</i>	
THE EFFECT OF THE IMPEDANCE HEAD ON THE MECHANICAL-ACOUSTICAL RECIPROCAL DEVICES PROPERTY	6684
<i>Lu Ling, Sun Hongling, Yin Yao, Yang Jun</i>	

SOUND PULSE SIGNAL PROCESSING METHOD FOR FAULT DETECTION.....	6690
<i>Tian Hao, Yan Zhaoli, Yang Jun</i>	
RESEARCH ON THE VIBRATION ISOLATION EFFECT BASED ON THE IMPEDANCE RELATION OF COMPLEX MECHANICAL SYSTEM.....	6697
<i>Wu Wuhui</i>	
ANALYSIS OF SOUND ABSORPTION CHARACTERISTICS OF PIEZOELECTRIC FILM SHUNTED WITH ELECTRIC CIRCUITS USING EQUIVALENT MECHANICAL MODEL.....	6705
<i>Akasaka Shuichi, Otomo Shunsuke, Asai Shigeo</i>	
PASS-BY NOISE TESTS BY MEANS OF CIRA ACOUSTIC ANTENNAS SYSTEM.....	6711
<i>Diodati Gianluca, Quaranta Vincenzo, Tarallo Francesco, Camastra Francesco, Fiorillo Vincenzo</i>	
POSITION AND VELOCITY MEASUREMENT OF A MOVING OBJECT BY PULSE COMPRESSION USING ULTRASOUND CODED BY PREFERRED-PAIR M-SEQUENCES.....	6719
<i>Hirata Shinnosuke, Yamanaka Kota, Hachiya Hiroyuki</i>	
PHOTO-INTERRUPTER AS DISPLACEMENT MEASUREMENT SENSOR CAPABLE OF WORKING AT LOW TEMPERATURES AND UNDER VACUUM.....	6726
<i>Ziemianski Daniel</i>	
STUDY ON LOW FREQUENCY EXCITATION CHARACTERISTICS OF MARINE PROPULSION SYSTEM-BASED NOISE SOURCE.....	6730
<i>Wu Wuhui</i>	
ACOUSTIC DISTANCE MEASUREMENT BASED ON THE INTERFERENCE BETWEEN TRANSMITTED AND REFLECTED WAVES USING CROSS-SPECTRAL METHOD BY INTRODUCING ANALYTIC SIGNAL OF LINEAR CHIRP AND HILBERT TRANSFORM FILTER.....	6737
<i>Sakaguchi Kosuke, Honda Shinya, Shinohara Toshihiro, Uebo Tetuji, Nakasako Noboru</i>	
ACOUSTIC CHARACTERISTICS OF BIVALVE AND POSSIBILITY OF AUTOMATICALLY DISCRIMINATING DEFECTIVE BIVALVE USING ACOUSTIC SIGNAL.....	6745
<i>Murata Shinji, Shinohara Toshihiro, Nakano Tomofumi, Nakasako Noboru</i>	
AN IMPLEMENTATION ON PROTOTYPE COMPACT SYSTEM OF TWO-CHANNEL ACOUSTIC DISTANCE MEASUREMENT METHOD MEASURABLE FROM 0M BASED ON THE STAND-ING WAVE CONSIDERING DIRECT CURRENT COMPONENT AND PHASE SPECTRUM.....	6753
<i>Song ChangRyung, Shinohara Toshihiro, Uebo Tetsuji, Nakasako Noboru</i>	
ACOUSTIC DISTANCE MEASUREMENT BASED ON PHASE INTERFERENCE BETWEEN TRANSMITTED AND REFLECTED WAVES AND POSITION ESTIMATION BY USING KINECT V2'S MICROPHONE ARRAY.....	6761
<i>Oda Ryohei, Shinohara Toshihiro, Uebo Tetsuji, Nakasako Noboru</i>	
INTEGRATED ACOUSTIC DESIGN IN THE ARCHITECTURE OF HELLENIC DRAMA THEATRES OF THE 19TH AND 20TH CENTURY.....	6769
<i>Sotiropoulou Alexandra, Karagiannis Ioannis, Margaris Odysseas, Karavoglou-Schismenos Georgios, Fotomaras Georgios</i>	
DIFFUSION CONTROL FOR MULTI-CHANNEL ANC SYSTEMS USING FILTERED-X ALGORITHMS.....	6778
<i>Chu Yijing, Mak Cheuk-Ming</i>	
INVESTIGATING HOW PREDICTIONS OF REVERBERATION TIME CAN BE AFFECTED BY INCORRECT ABSORPTION COEFFICIENT ASSUMPTIONS.....	6785
<i>Yule Lawrence, Ford Ben</i>	
GUIDELINES FOR PREDICTION AND EVALUATION OF ACOUSTIC IMPACT ON UNDERWATER FAUNA.....	6793
<i>Glisser Max, Gomez Ismael, Padilla Camilo, Priede Patricio</i>	
USING A SMARTPHONE APPLICATION TO PERFORM A FAST QUALITATIVE NOISE EXPOSURE EVALUATION IN A MINE SITE.....	6801
<i>Corral Luis, Aumond Pierre, Oyarzo Luis C.</i>	
IMPLEMENTATION OF A LOW COST REMOTE FAILURE MONITORING SYSTEM FOR SPEAKER LINES IN A SHOPPING MALL.....	6805
<i>Corral Luis, Aumond Pierre, Oyarzo Luis C.</i>	
Author Index	

TIME-DOMAIN STRUCTURAL VIBRATION SIMULATIONS BY SOLVING THE LINEAR ELASTICITY EQUATIONS WITH THE DISCONTINUOUS GALERKIN METHOD

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In the field of building acoustics, an efficient solution of the linear elasticity equations for vibro-acoustic problems is of interest. The focus of this work is on the structural part, with plate vibration problems in particular. The linear elasticity equations in the stress-velocity formulation are solved in the time-domain for the three-dimensional plate problem. The numerical solution is obtained through the Runge-Kutta discontinuous Galerkin method, which has the potential to be highly parallelizable and thereby computationally very efficient. Numerical aspects of applying the discontinuous Galerkin method to this problem are discussed, especially on the force excitation and the boundary conditions of the plate problem. The accuracy of applying the discontinuous Galerkin solution is presented by comparing its results to results from analytical solutions. Several scenarios of plate variations with different boundary conditions are simulated to demonstrate the capabilities of the method.

Keywords: plate vibration, discontinuous Galerkin method, low frequencies, time domain

1. Introduction

To design a proper sound insulation, prediction of sound transmission through building components is needed. Sound transmission through a panel is frequently predicted using two analytical approaches. The first approach calculates sound transmission by simplifying the dynamics of the fluid or the structure. Often, this approach idealises the impinging sound wave to the structure as a plane wave or assuming a diffuse field condition. The calculation models of this approach include plane wave transmission through an infinite plate, and transmission of a diffuse sound field through a baffled plate [1]. Moreover, at high frequencies, when the structural field is also a diffuse field, the statistical energy analysis (SEA) could be utilized to calculate sound transmission. This approach is used extensively in many engineering practice since it has a low computational cost. However, when the coupling between structure and fluid is strong, for instance at low frequencies, the first approach is not appropriate. This leads to the second approach where the dynamics of the fluid in a cavity is calculated and coupled with the dynamics of the structure. One way to apply the second approach is by representing the unknown variables in each subsystem using a modal expansion method [1] [2]. Afterwards, continuity conditions in the fluid-structure interface are satisfied. In case of light fluid loading, structural mode shapes can be obtained *in-vacuo*, and room mode shapes can be obtained by assuming the structure is rigid.

The more general way to conduct the second approach is by numerically solving the structure and fluid problem using the same variables for both media, i.e. the displacement/velocity and stress terms [3]. This methodology can be applied, for instance, using linear elasticity equations. There are some advantages of using the linear elasticity equations to solve the sound transmission problem. For example: a separate model between thin or thick structure is not needed, and changes in cross section area due to stiffeners, junctions, or any discontinuities could be treated directly in the model. In this paper, as a first step to solve the fluid-structure interaction problem to model sound insulation of a complex building structure, the dynamics of a plate as a three-dimensional structure are modelled by solving the linear elasticity equations using a numerical method.

The linear elasticity equations have been used frequently to model seismic wave problems, examples of numerical solutions in the time domain can be found in the work of Vireux using the finite difference method [4], and in the work of Dumbser using an arbitrary high-order derivatives discontinuous Galerkin (DG) method [5]. In the field of building acoustics, the linear elasticity equations have been used to model a floor system, and a numerical solution has been developed by Toyoda using the finite difference method [6]. In this paper, using the same equations for the plate vibration problem, the nodal DG method is used to get the solution. This method is in particular of interest as it is very favourable to carry out DG calculations by a parallel implementation, opening opportunities of solve real-world problems in a reasonable computation time. Furthermore, hybrid approach on nodal DG with Fourier Pseudospectral time-domain has been conducted by Pagán Muñoz to solve the acoustic propagation problem in fluid [7], which has the possibility to be coupled with the current structural vibration problem. The nodal DG is one method of applying the DG method; it is developed by Hesthaven and Warburton [8] and has been used widely to solve electromagnetic and fluid mechanics problems. In the next section, brief descriptions of the method including source term and boundary conditions are described. Finally, the plate mobility solution for different sets of boundary conditions are presented and compared with the thin plate solution.

2. Formulation

2.1 Linear Elasticity Equations

In solid isotropic media, linear vibrations can be modelled by equations of motion and constitutive equations; this set of equations is known as the linear elasticity equations. By having the time derivative of the stress-strain constitutive equations, the isotropic linear elasticity equations can be written in the stress-velocity form using three-dimensional Cartesian coordinates as:

$$\frac{\partial \mathbf{q}}{\partial t} + \nabla \cdot (\mathbf{A} \mathbf{q}) = \mathbf{g}, \quad (1)$$

$$\mathbf{A} = \mathbf{A}_x n_x + \mathbf{A}_y n_y + \mathbf{A}_z n_z,$$

$$\mathbf{A} = \begin{bmatrix} 0 & 0 & 0 & -n_x/\rho & 0 & 0 & -n_z/\rho & 0 & -n_y/\rho \\ 0 & 0 & 0 & 0 & -n_y/\rho & 0 & 0 & -n_z/\rho & -n_x/\rho \\ 0 & 0 & 0 & 0 & 0 & -n_z/\rho & -n_x/\rho & -n_y/\rho & 0 \\ -(\lambda + 2\mu)n_x & -\lambda n_y & -\lambda n_z & 0 & 0 & 0 & 0 & 0 & 0 \\ -\lambda n_x & -(\lambda + 2\mu)n_y & -\lambda n_z & 0 & 0 & 0 & 0 & 0 & 0 \\ -\lambda n_x & -\lambda n_y & -(\lambda + 2\mu)n_z & 0 & 0 & 0 & 0 & 0 & 0 \\ -\mu n_z & 0 & -\mu n_x & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -\mu n_z & -\mu n_y & 0 & 0 & 0 & 0 & 0 & 0 \\ -\mu n_y & -\mu n_x & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix},$$

$$\mathbf{q} = \begin{bmatrix} v_x & v_y & v_z & \tau_{xx} & \tau_{yy} & \tau_{zz} & \tau_{xz} & \tau_{yz} & \tau_{xy} \end{bmatrix}^T,$$

$$\mathbf{g} = [g_x \ g_y \ g_z \ 0 \ 0 \ 0 \ 0 \ 0 \ 0]^T,$$

with $\mathbf{q}$ the vibration variables vector, $\mathbf{v}_i$ the velocity vector, τ_{ij} the stress tensor, and $\mathbf{g}$ the body force vector. $\mathbf{A}$ is the fluxes Jacobian which includes the material property: the density ρ , and the Lamé parameters λ, μ . The coefficients n_x, n_y, n_z are the unit normal of the control surface. The problem specification is completed by defining the problem domain, initial and boundary conditions. This set of equations consists of nine variables, and all derivative operators are of first order. In this study, the solution of the linear elasticity equations is obtained by evaluating the spatial differential operator using the nodal DG method, and integrating the time differential operator using the Runge-Kutta method.

2.2 Nodal Discontinuous Galerkin Method

To solve partial differential equations, the DG method discretizes the problem domain into several discontinuous conforming elements. On each element D , the problem's variational form is satisfied to obtain a solution where the unknown variables are approximated using a combination of basis functions. Moreover, the DG method solves the integration of numerical fluxes along the boundaries ∂D using a Riemann solver. In this study, the nodal approach of the DG method as presented by Hesthaven and Warburton is applied [8]. This approach uses the strong variational form and Lagrange interpolating polynomials $\varphi_p(\mathbf{x})$ as the basis function. For the local solution, unknown variables are expressed using summation of the basis function as:

$$\mathbf{q}_h(\mathbf{x}, t) = \sum_{p=1}^{N_p} \mathbf{q}_h(\mathbf{x}_p, t) \varphi_p(\mathbf{x}), \quad (2)$$

where $\mathbf{q}_h$ is the local solution of Eqs. (1) for unknown variables $\mathbf{q}$, subscript p is the index of the basis function, and N_p is the maximum order of the basis function that is used. Using the interpolating polynomials as basis function, nodal DG distributes N_p number of nodes in each element. The details on the nodal distribution can be seen in the work of Hesthaven [8]. To obtain the strong form, Eqs. (1) are multiplied with a test function, where in Galerkin method the test function is same as the basis function. Afterward, integration over the volume V of each element is applied twice over the element:

$$\int_D \left[\frac{\partial \mathbf{q}_h}{\partial t} + \nabla \cdot (\mathbf{A} \mathbf{q}_h) \right] \varphi_p dV = \int_D \mathbf{g}_h \varphi_p dV - \int_{\partial D} \mathbf{n} \cdot [\mathbf{f}^* - \mathbf{A} \mathbf{q}_h] \varphi_p dS, \quad (3)$$

where $\mathbf{f}^*$ is the numerical flux, and $\mathbf{n}$ is the normal vector to the element boundary ∂D . In this study, to solve the Riemann problem a numerical flux from Godunov's method is used. The derivation of this flux can be seen in [5] [9], and reads as:

$$\mathbf{f}^* = \mathbf{R} \Lambda^+ \mathbf{R}^{-1} \mathbf{q}^- + \mathbf{R} \Lambda^- \mathbf{R}^{-1} \mathbf{q}^+, \quad (4)$$

where $\mathbf{R}$ are the right eigen-vectors of matrix $\mathbf{A}$, Λ^+ are the positive eigenvalues of $\mathbf{R}$, Λ^- are the negative eigen-values of $\mathbf{R}$, $\mathbf{q}^-$ are the element vibration variables on the element boundary, and $\mathbf{q}^+$ are the neighbour elements vibration variables that coincide with $\mathbf{q}^-$. By inserting Eq. (2) to Eq. (3), and exploring the orthonormal properties of the basis function, the final semi-discrete form of Eqs. (1) can be written as:

$$\mathbf{M}^D \frac{\partial \mathbf{q}_h}{\partial t} + \sum_{j=x,y,z} \mathbf{K}_j \mathbf{A}_j \mathbf{q}_h = \mathbf{M}^D \mathbf{g}_h - \sum_{i=1}^b \mathbf{M}^{\partial D_i} (\mathbf{f}^* - \mathbf{A} \mathbf{q}_h), \quad (5)$$

where $\mathbf{M}^D$ is the mass matrix of the element, $\mathbf{K}_j$ is the stiffness matrix on each spatial derivative, $\mathbf{M}^{D_i}$ is the mass matrix of the element face i , and b is the number of faces on each element. These matrices are obtained by transforming all elements into a reference element, and pre-calculated for each element before time integration is conducted. Having this form, time integration is applied to march forward from the initial conditions. In this work, the low storage Runge-Kutta method of order 4 and with 5 stages is used. More details on the nodal DG method can be found in [8].

3. Plate vibration application

3.1 Problem setting

In this section, the plate vibration problem is described. There are three plates with a different thickness $h = 0.12\text{m}$; 0.08 m ; and 0.04 m . Each plate is made of concrete with Young's modulus 33.7 GPa , density 2300 kg/m^3 , Poisson's ratio 0.225 , and area $1.8 \times 1.2\text{ m}^2$. The plate is illustrated in Fig. 1 using a Cartesian coordinate system with the origin at $(0,0,0)$. The objective of the problem is to get the transfer mobility between force located at $(0.42, 0.99, h)\text{ m}$ (marked as a blue dot) and velocity located at $(1.35, 0.99, h)\text{ m}$ (marked as a red dot).

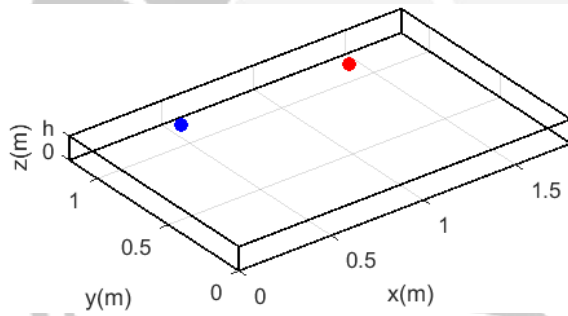


Figure 1: Illustration of plate, and source and receiver position

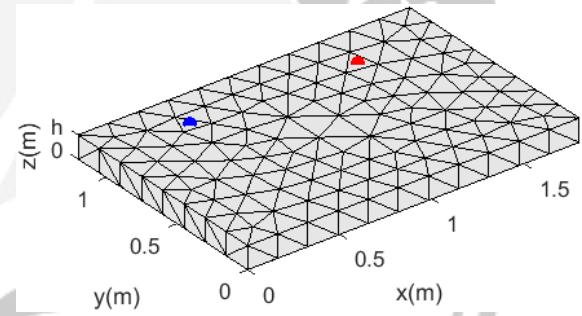


Figure 2: Illustration of the used discretization.

The force function is a Ricker wavelet as defined in Eq. (6) with centre frequency $f_c = 500\text{ Hz}$. This frequency is taken, since the interest frequency range is below 1 kHz . In the simulation, a time delay $t_d = 5\text{ ms}$ is given to get a smooth force function.

$$\tau_{zz}(\mathbf{x}_0, t) = \left(0.5 - (\pi f_c (t - t_d))^2\right) \exp\left(-(\pi f_c (t - t_d))^2\right). \quad (6)$$

Table 1: Specification of boundary conditions in each case

Face	Free conditions	Clamped conditions	Simply supported conditions
$\partial\Omega_{top}$	$\tau_{iz} = 0$	$\tau_{iz} = 0$	$\tau_{iz} = 0$
$\partial\Omega_{bot}$	$\tau_{iz} = 0$	$\tau_{iz} = 0$	$\tau_{iz} = 0$
$\partial\Omega_{edge1}$	$\tau_{ix} = 0$	$v_i = 0$	$v_y = 0; v_z = 0; \tau_{xx} = 0;$ $\tau_{yy} = 0; \tau_{zz} = 0; \tau_{yz} = 0.$
$\partial\Omega_{edge2}$	$\tau_{iy} = 0$	$v_i = 0$	$v_x = 0; v_z = 0; \tau_{yy} = 0;$ $\tau_{xz} = 0; \tau_{xx} = 0; \tau_{xz} = 0.$

To complete the problem definition, boundary conditions should be ascribed to each plate face. The plate boundary conditions are given in three sets of cases: free conditions, clamped conditions, and simply supported conditions. The description of each condition case is given in Table 1. Where $\partial\Omega_{top}$ is the plate top face at $z = h$, $\partial\Omega_{bot}$ is the plate bottom face at $z = 0$, $\partial\Omega_{edge1}$ are the plate edge faces at $x = 0$ and $x = 1.8$, and $\partial\Omega_{edge2}$ are the plate edge faces at $y = 0$ and $y = 1.2$ with index i equal to x, y or z . To summarize, there are nine plate examples varying with thickness and boundary conditions. The details considering the simply supported conditions on a three-dimensional plate can be seen in the work of Srivinas [9].

3.2 Numerical setting

The plate is discretized using unstructured tetrahedral elements that are generated by the Gambit mesh generator. The maximum element size is 0.16 m for every plate case, and a mesh illustration can be seen in Fig. 2. In every numerical calculation, basis functions with maximum order three are used. By this setting, 20 nodes are created in each element. In the nodal DG, to update the solution on each element, the neighbour element information q^+ is needed. For nodes on the boundary faces, the value of q^+ is obtained from q^- and the condition at the surface, either a boundary condition from Table 2 or the source function. The methodology in defining q^+ is quite similar to the finite volume methodology while defining the ghost nodes. In Table 2, the counterpart of Table 1 as the numerical boundary condition settings is presented. In this table, the q^+ on each set of faces and case are given, with each index i, j equal to x, y or z .

Table 2: Boundary conditions settings in the nodal DG

Face	Free conditions	Clamped conditions	Simply supported conditions
$\partial\Omega_{top}$	$\tau_{iz}^+ = -\tau_{iz}^-; v_i^+ = v_i^-$	$\tau_{iz}^+ = -\tau_{iz}^-; v_i^+ = v_i^-$	$\tau_{iz}^+ = -\tau_{iz}^-; v_i^+ = v_i^-$
$\partial\Omega_{bot}$	$\tau_{iz}^+ = -\tau_{iz}^-; v_i^+ = v_i^-$	$\tau_{iz}^+ = -\tau_{iz}^-; v_i^+ = v_i^-$	$\tau_{iz}^+ = -\tau_{iz}^-; v_i^+ = v_i^-$
$\partial\Omega_{edge1}$	$v_i^+ = v_i^-; \tau_{ix}^+ = -\tau_{ix}^-; \tau_{yy}^+ = \tau_{yy}^-;$ $\tau_{yz}^+ = \tau_{yz}^-; \tau_{zz}^+ = \tau_{zz}^-.$	$\tau_{ij}^+ = \tau_{ij}^-; v_i^+ = -v_i^-$	$v_y^+ = -v_y^-; v_z^+ = -v_z^-; \tau_{ii}^+ = -\tau_{ii}^-; \tau_{yz}^+ = -\tau_{yz}^-;$ $\tau_{xz}^+ = \tau_{xz}^-; \tau_{xy}^+ = \tau_{xy}^-; v_x^+ = v_x^-.$
$\partial\Omega_{edge2}$	$v_i^+ = v_i^-; \tau_{iy}^+ = -\tau_{iy}^-; \tau_{xx}^+ = \tau_{xx}^-;$ $\tau_{xz}^+ = \tau_{xz}^-; \tau_{zz}^+ = \tau_{zz}^-.$	$\tau_{ij}^+ = \tau_{ij}^-; v_i^+ = -v_i^-$	$v_x^+ = -v_x^-; v_z^+ = -v_z^-; \tau_{ii}^+ = -\tau_{ii}^-; \tau_{xz}^+ = -\tau_{xz}^-;$ $v_y^+ = v_y^-; \tau_{yz}^+ = \tau_{yz}^-; \tau_{xy}^+ = \tau_{xy}^-.$

To insert the force, since it is acting on the boundary of the plate, the normal stress component $\tau_{zz}(\mathbf{x}_s, t)$ is defined on the face of the element where the force is located. First, the mesh face where the impact point is located should be identified. Then, following the LeVeque's work in finite volume method [10], the stress component of nodes at the face $\mathbf{x}_s$ is expressed using $\tau_{zz}^+(\mathbf{x}_s, t) = 2g_z(t)/A_0 - \tau_{zz}^-(\mathbf{x}_s, t)$, with face area A_s and g_z the body force in N. Other stress components are not specified, which lead to the following expressions: $\tau_{xx}^+(\mathbf{x}_s, t) = \tau_{xx}^-(\mathbf{x}_s, t)$, $\tau_{yy}^+(\mathbf{x}_s, t) = \tau_{yy}^-(\mathbf{x}_s, t)$, $\tau_{xz}^+(\mathbf{x}_s, t) = \tau_{xz}^-(\mathbf{x}_s, t)$, $\tau_{yz}^+(\mathbf{x}_s, t) = \tau_{yz}^-(\mathbf{x}_s, t)$, and $\tau_{xy}^+(\mathbf{x}_s, t) = \tau_{xy}^-(\mathbf{x}_s, t)$. It should be noted here that the force is acting on a finite area and not a point, since for a point the normal stress cannot be defined. Another approach is to apply a varying stress distribution on the area with maximum stress in a point of force insertion, but to fulfil the current objective and frequency range, the constant distribution is sufficient.

3.3 Thin plate reference

To validate the nodal DG method, the transfer mobilities of the plate examples are calculated using the thin plate theory, and the results are taken for comparison. The thin plate theory calculates the bending wave response of a plate due to a transverse point force using a modal expansion approach. This modal function should satisfy the given boundary conditions. The plate mobility by thin plate theory is given by:

$$\frac{v_z(x_r, y_r)}{F_z(x_s, y_s)} = i\omega \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{\Phi_{m,n}(x_r, y_r) \Phi_{m,n}(x_s, y_s)}{\Lambda_{m,n} [\omega_{m,n}^2 - \omega^2]}, \quad (6)$$

with $\Phi_{m,n}$ the mode function of the plate, $\Lambda_{m,n}$ the norm of the plate, $\omega_{m,n}$ the natural angular frequency, ω the force angular frequency, x_r, y_r the location of the receiver point, and x_s, y_s the location of the source point. The indices m, n represent the numbers of the eigenmodes $\Phi_{m,n}$ in the x, y . In this work, the details of the modal functions for the given set of boundary conditions, and the natural angular frequencies, are adopted the work by Gardonio and Elliot [11].

4. Results and discussion

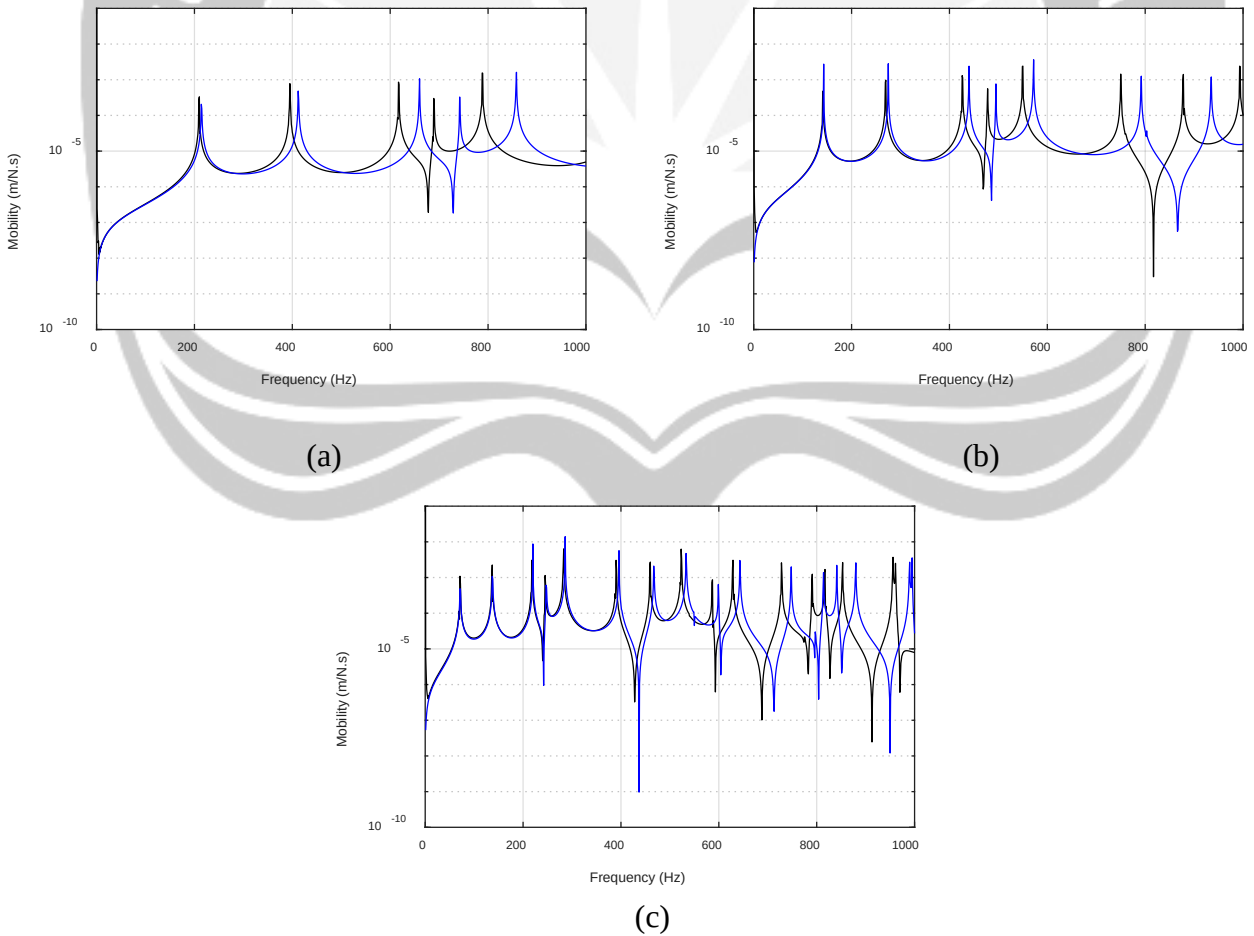
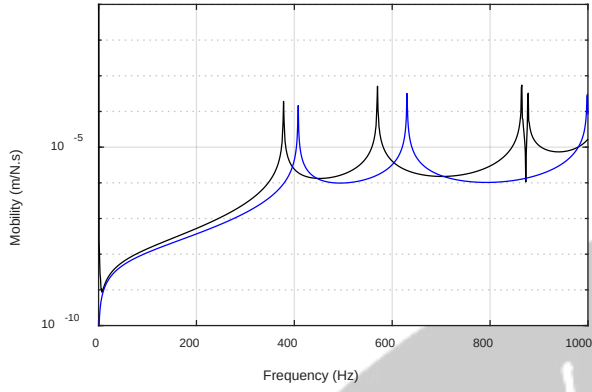
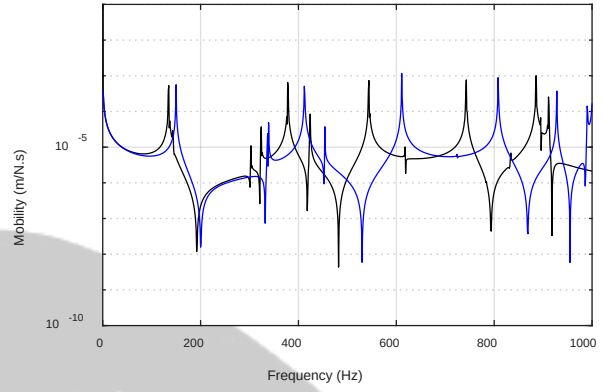


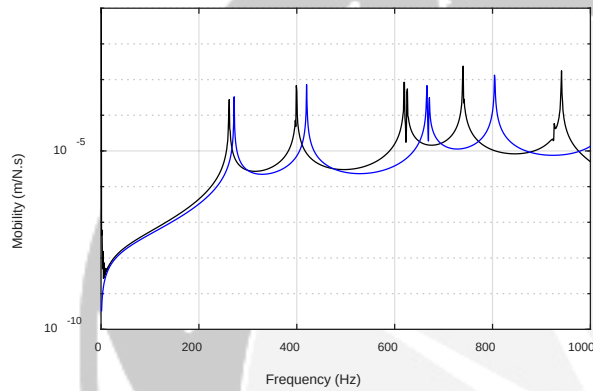
Figure 3: Plate mobility with simply supported boundary conditions for $h =$ (a) 0.12m, (b) 0.08m, (c) 0.04m. Black line: nodal DG calculation, blue line: thin plate calculation.



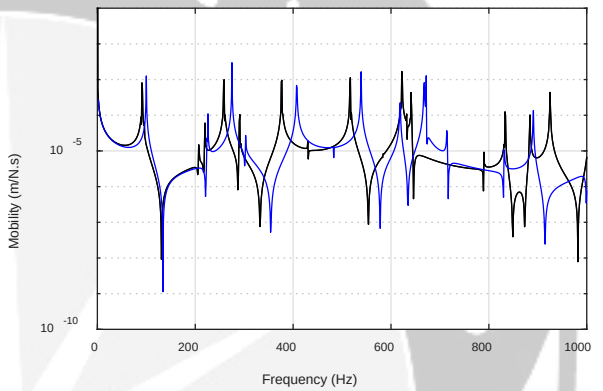
(a)



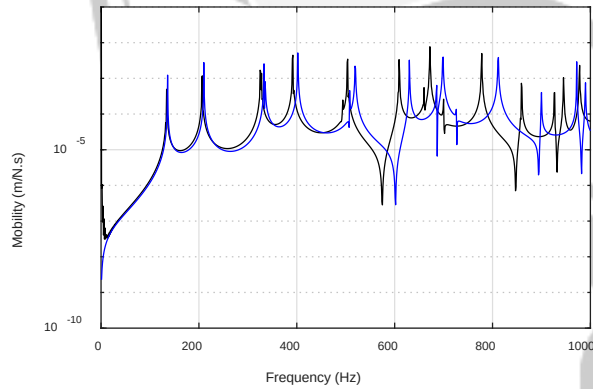
(a)



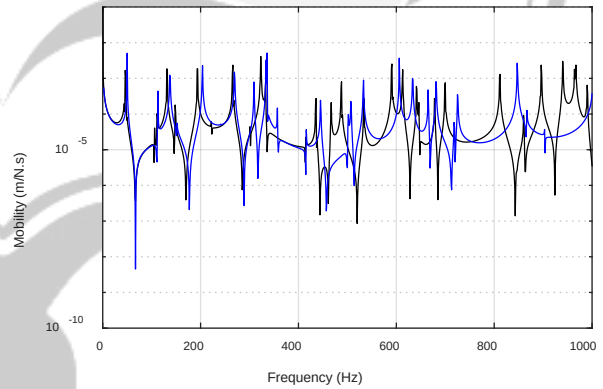
(b)



(b)



(c)



(c)

Figure 4: Plate mobility with clamped boundary conditions, for $h =$ (a) 0.12m, (b) 0.08m, (c) 0.04m. Black line: nodal DG calculation, blue line: thin plate calculation.

Figure 5: Plate mobility with free boundary conditions, for $h =$ (a) 0.12m, (b) 0.08m, (c) 0.04m. Black line: nodal DG calculation, blue line: thin plate calculation.

The nodal DG results shown in this section are obtained by having Fourier transformation of 1 s time domain numerical calculations. From Fig. 3 and Fig. 4, it can be seen that the DG results are in good agreement with the thin plate reference in the low frequencies region and for thinner plate. However, it can be seen that the discrepancy between results is increasing, as the frequency is getting higher. This discrepancy is expected, since the thin plate theory underestimates the plate inertia

and flexibility, which resulted in an overestimation of natural frequencies [12]. Results for the plate with free boundary conditions is shown in Fig. 5, showing a larger discrepancy than in figures 3 and 4. These discrepancies happen since the linear elasticity equations allow a variation of the displacement over the z -direction, which induces more modes. It should be noted that damping is not introduced into the DG model and in the thin plate reference. This creates sharp resonance peaks in the results.

5. Conclusions

To model vibrations in plates, a nodal time-domain discontinuous Galerkin method is presented to solve the linear elasticity equations. The free, clamped, and simply supported boundary conditions have been implemented in DG methodology, along with an external force insertion applied as a normal stress on the boundary. For all plate cases, the results show a reasonable agreement with the thin plate theory especially at low frequencies and at smaller thickness. To get a more accurate validation, the nodal DG solution should be compared to a thick plate theory. Further work will contain an extension to the fluid media such that fluid-structure problems in acoustics can be solved. In addition, an acceleration of the DG method by a parallel implementation will make this method highly useful for industrial applications.

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